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LESSONS FROM ARMY SYSTEM DEVELOPMENTS

VOLUME II – CASE STUDIES

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13. ABSTRACT (Maximum 200 words) This report documents the results of a research project of several years' duration which employed a structured case study approach to examine the history and processes that had resulted in the introduction of a number of technology-based Army systems in time to make a positive contribution to the outcome of Desert Storm. Volume II of the report contains the 15 case studies that were developed on systems ranging from the M829A1 "silver bullet" to the GUARDRAIL Common Sensor and the APACHE attack helicopter. The case studies were developed through the use of structured interviews with key participants from the government/contractor team that developed each system. In addition to the case studies, this process resulted in collection of a common set of data for the systems studied which could then be analyzed to identify factors contributing to successful system development. That analysis is contained in Volume I of this report. Two of the 15 case studies examined systems which might have been useful on the battlefield (based on the views of Army technical leaders), but which failed to successfully complete development. The intent of including failures in the research was to provide a basis for distinguishing factors which contributed to both successful and unsuccessful system developments. While they are useful for the qualitative lessons they offer, two cases are inadequate for quantitative analysis and most analysis focuses on the 13 successful cases. It is therefore an assessment of contributors to the relative degree of success.				
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INTRODUCTION

Background

Desert Storm was one of the most remarkable military conflicts ever fought. Its uniqueness is found in its one-sidedness: what could have been a protracted small war against an Iraqi force of 600,000 troops was concluded in 17 days of ground combat, with only 36 troops lost to enemy action. This was an historic triumph of training, organization, logistics and technology. In the specific case of the US Army, a number of new military systems, incorporating sophisticated technology, made their first significant battlefield appearance in Desert Storm.

This research project focuses on the process that brought that technology to the battle field in order to develop insights for planning and organizing for the continued generation of technology-based systems. In this first decade of the 21st Century it is evident that the system of defense laboratories, contractors and technology programs that produced Desert Storm's technology is being fundamentally changed. The end of the Cold War, the current focus on the Global War on Terrorism, and the perceived absence of other significant military threats to the security of the nation are, to some significant extent, resulting in the dismantling of the organization and process of U.S. defense technology development that produced the success of Desert Storm.

This work took advantage of a window of opportunity. Desert Storm is now distant enough to allow perspective, and to enable the use of widely known information about technologies that were previously classified. At the same time, its history is recent enough that the key players in the development of this technology are still available to provide their recollections and insights. New research can now examine the development of military systems used in Desert Storm to provide insight into the keys to success and failure at that time, capturing lessons that might inform the management of Army technology development in the future.

Case Study Methodology

Research Approach

As noted above, the basic intent of this research was to examine the history and processes that had resulted in the introduction of a number of technology-based Army systems in time to make a positive contribution to the outcome of Desert Storm. In order to be able to examine as many different systems as possible within the constraints of the funding available for the study, the authors proposed that a significant portion of the work would be performed using "free labor"; experienced defense personnel enrolled in military and academic institutions would execute the data collection portion of the research (as the subject for a thesis or research paper). Each was to use a consistent framework for collecting and presenting data; this framework, in the form of a "Case Study Checklist"-a research questionnaire, was prepared by the authors. This approach, referred to sometimes as a "structured thesis," has been used successfully at MIT for many years. It leaves the student important latitude to identify important issues not in the guiding structure, and the opportunity to reach independent conclusions while still contributing to a unified research structure. This construct

intended to benefit from the maturity and experience of senior students who were already familiar with defense processes and systems.

This planned student involvement approach was implemented with partial success in this project. Research for one-third of the cases was carried out by students who matched the a priori experience and background assumptions. Two of these students used their research on this project as the basis of Masters theses which they wrote during their graduate study at the Naval Postgraduate School, under collaborative arrangements with Postgraduate School faculty developed by the authors. Research on another third of the cases was carried out by graduate students at the University of Alabama in Huntsville who did not have previous knowledge of defense processes and systems. One of the authors attempted to compensate for this lack of background by providing a series of tutorial sessions on the defense acquisition process and organizational relationships during the course of their work. Also, one of these students researched three cases, over a two year period, and was able to use the acquisition process experience he gained in developing the first case to advantage on the latter two cases. The final third of the cases were researched by Professor Dan Sherman, of the University of Alabama in Huntsville faculty; Dr. Sherman was knowledgeable of Army acquisition processes and organizations from his prior research experience. Project resources originally earmarked to support collaboration with faculty at a larger number of educational institutions were reallocated to fund Dr. Sherman's involvement.

In short, it proved more difficult than anticipated to find Army military or civilian students enrolled in programs which required a research project, who could be interested, on a voluntary basis, in participating in this effort. As a result, all 15 cases were researched by individuals with ties of one sort or another to Huntsville, Alabama organizations, and (as will be discussed) their choice of systems to research resulted in somewhat greater coverage of missiles and aviation related systems.

Research Products

Each individual researching a system (case) carried out interviews using the structured questionnaire with key participants from the government and contractor project management teams which had been responsible for developing, producing and fielding that system. The researcher was then responsible to synthesize two products, which he provided to the authors. The first product was an "integrated" questionnaire that documented his view of the most accurate answers to the questions, based on the more detailed interviews he had conducted, and giving appropriate weight to the interviewee best situated to know "truth" in a particular case. For example, in the event of disagreement in the individual responses to questions about the functioning of the contractor's design teams, researchers were instructed to give greater weight to the views of the contractor program manager. The results of analysis of these answers across the systems studied appear in volume I of this report.

The second product was a system case study, documenting in narrative form his insights on the key issues discussed during the interviews. At a minimum, he was asked to discuss the issues dealt with in the research questionnaire, but was encouraged to examine other issues in which he had particular interest, or which had been raised by the interview subjects. Development of this series of system case studies was intended to significantly increase the

number available for use by defense acquisition students and educators. For several systems (FOG-M, MLRS, PATRIOT), these new case studies explored issues that were substantially different from those contained in prior cases on the same systems, deepening the documentary coverage for that particular system. The system case studies appear in the following chapters of this volume (Volume II) of the report.

Research questionnaire

As was previously noted, use of a research questionnaire to guide the interviews was a critical aspect of the research methodology. This questionnaire was designed by the authors to provide coverage of a number of development process, organizational relationship, critical technology maturity and other issues that either the authors' prior experience or the management literature suggested might be relevant to determining the relative success of projects. Some questions that were in common with a research instrument successfully used by one of the authors in a prior study of aerospace research projects. Table 1.1 contains a listing of research questions incorporated into the questionnaire.

<u>Question</u>	<u>System</u>	<u>Technology</u>	<u>Questionnaire</u>
Outcomes?	X	X	O1-O10
Production readiness?	X		Page 1, T3,H6, B4-B6, B8
Technology readiness?	X	X	Page 1, T5-T7
Importance of technology to prime?		X	Page 1; T4
Familiarity of prime with technology?		X	Page 1; T2,T3
Role of gov't S&T organization?	X	X	T8-T10, B11 Page 1
Role of S&T organization that developed technology?	X	X	Page 1 T8-T10
Timeline?	X		Page 1
Difficulties in integrating technology?		X	T3, H3, B1, B4-B8
User support? (or role of user?)	X		D18, F5-F6,W3-W5
Key Issue for PM?	X		I2
Timely problem disclosure?	X		D12, D16,D19
Requirements stability?	X		F7,W6,B13
Test approach used?	X	X	V1-V15
IPT approach used?	X		H2,H4-H5, D7, D9, D1, D13, D14, D16, D19, F4
Proper staffing of IPT?	X		H3, D3-D6,D8, D10
Design to manufacturing linkage?	X	X	F1-F3, F10-F13, W1-W2, W16-W18
Funding stability?	X		H1, D11, B2
Design to supplier linkage?	X	X	F20-F23, W26-W28, B10

Table 1.1 – Research Questions Examined

This list includes whether the question applies at the technology or system level because in addition to questions about the system as a whole, a set of questions focused on the component systems and technologies. The draft questionnaire was tested by four former Army system project managers (whose former system responsibilities were not included in the systems chosen for this research project). Their responses provided valuable suggestions for clarifying the wording of a few of the questions, which was done in the final version, and they found that completing the questionnaire could be done in about 30 to 45 minutes. The final questionnaire is provided as an APPENDIX in Volume I of this report, and has been modified by inserting the responses to the questions.

Systems Studied

As was earlier noted, the common feature of the system developments studied in this research is that each system first was employed in a significant way on the battlefield in Desert Storm. That, in turn, meant that for the most part development began on these systems during the 1980s. It was the intent that the systems studied include examples from the broad array of military systems for which the (original) research sponsor- The Army Materiel Command (AMC)-had responsibility. To achieve that intent, the following process was used to develop a list of candidate systems from which the researchers could select systems to study:

1. Each Director of an AMC Research, Development and Engineering Center was asked to nominate candidate systems from his commodity area (e.g. missiles, aviation, communications) that met the criterion of having first been successfully used in a significant way in Desert Storm. Each Director was also encouraged to discuss this question with project managers that his organization supported, and include their input. Each was further asked to nominate any systems which, in their judgment, would have been militarily useful in Desert Storm, but had failed to complete development. (Note: this process resulted in relatively few such failures being identified.)
2. The list of candidate systems that resulted was discussed with the AMC Deputy Commander (who was a veteran of Desert Storm) and his civilian Senior Executive Service deputy. Together they divided the approximately 40 candidate systems into two groups, reflecting priority for research attention. The systems studied in this project were taken from the first priority group.
3. As students were recruited to participate in developing case studies, they were initially allowed to choose systems on a "first come, first served" basis. Presumably because the students were affiliated with Huntsville, Alabama organizations, this approach resulted in essentially complete coverage of the missiles and aviation-related systems. In order to broaden the coverage, Dr. Sherman was requested to select one of the failure-to-complete-development systems and two systems that were neither missiles nor aviation-related. Because of the missile and aviation selections of the early participants, later participants were also encouraged to select systems that broadened the coverage of the AMC commodity line. Table 1.2 summarizes pertinent information about the systems that were selected for study in this research project.

<u>System</u>	<u>Researcher</u>	<u>Commodity category</u>
APACHE attack helicopter	Ference	Aviation
TADS/PNVIS (target acquisition and designation/pilot's night vision systems)	Oelrich	Aviation
MLRS rocket system	Sherman	Missiles
ATACMS missile system	Romanczuk	Missiles
M40 chemical protective mask	Ruocco	Soldier support
Dismounted microclimate cooler Note: Did not enter production	Ruocco	Soldier support
Mounted microclimate cooler	Ruocco	Soldier support
M829-A1 armor-piercing kinetic energy tank ammunition	Mitchell	Ammunition
FOG-M (fiber optic guided missile) Note: Did not enter production	Sherman	Missiles
TOW-2A (Tube-launched missile)	Vessels	Missiles
AN/TAS 4 infrared night sight	Granone	Target acquisition
Joint Stars Ground Station	Sherman	Intelligence
Guardrail common sensor	Sherman	Intelligence
PAC-2 (PATRIOT anti-missile system)	Sherman	Missiles
HELLFIRE missile system	Johansen	Missiles

Table 1.2 – Systems studied

APACHE ATTACK HELICOPTER (AH-64)

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December 2002

This case study is one of a series developed under a research effort jointly funded by the U.S. Army Materiel Command and the Aviation and Missile Research, Development and Engineering Center. The information contained herein was originally included in a Naval Postgraduate School thesis, written by the author, which was approved for public release.

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Dateline: January 17, 1991 -- The largest military assault since D-Day began rather unceremoniously as eight Apache Attack Helicopters are led out into the desert by four Air Force MH-53J Pave Low Helicopters. Dubbed "Task Force Normandy", their mission, to open the door into Iraq, will signal the beginning of the Gulf War. This mission would mark yet another milestone in the long history of Army aviation.

A. BRIEF HISTORY OF ARMY AVIATION

1. Balloon Corps

The Union Army established the first "aviation unit" in the 1860's during the Civil War. Dubbed the "Balloon Corps of the Army of the Potomac"ⁱ, they used balloons to place observers above the battlefield to track enemy movement. This gave the commander a distinct advantage in this war of positioning. The Balloon Corps was later placed under the Signal Corps for the remainder of the war. It appears that there was considerable distrust for this new technology and the men who risked their lives to make it work. The Balloon Corps was disbanded shortly after the end of the war. This marked the first of several decisions to thwart Army Aviation in favor of ground troops.

Balloons were once again called into service in 1898 during the Spanish American War. During the fighting, the first U.S. airman was shot down in combat as his balloon was hit by enemy fire. Any hint of future Army aviation ended, as the balloons once again disappeared from the inventory at war's end.

Balloons have been used by the military since the turn of the century. They have evolved from one-man observation posts to highly sophisticated surveillance platforms. Balloons have also been used to drop ordnance in times of war. The use of balloons marked the unofficial beginning of Army aviation. Throughout the early years, aviation remained a fairly mundane communication asset in the Signal Corps. That was all to change with the onset of World War I.

2. Aircraft

On December 17, 1903, the first flight of a "heavier than air" craft took place at Kitty Hawk, North Carolina. The Wright brothers succeeded where many had failed and thus brought the world a little bit closer together. By August 1907, the Army Aeronautical Division was established to promote the use of aircraft in the military. In the fall of 1908, the Wright brothers build a heavier than air flying machine in response to Signal Corps request for proposals. During initial flight tests, Lt. Selfridge became the first aviation casualty, and the pilot, Orville Wright, sustained severe injuries, as the plane they were riding in fell to the ground. Wilbur Wright quickly repaired the plane and resumed flight-testing. He successfully demonstrated that the craft exceeded all Army requirements and Wright Brothers aircraft soon entered military service.

As the fledgling aviation fleet began to evolve, a daring young Russian inventor, Igor Sikorsky, was trying to prove his helicopter design. In 1909 Sikorsky got his craft off the ground, marking the first flight of a counter rotating, twin-bladed helicopter. As WWI approached, Sikorsky was forced to concentrate his efforts on large military

aircraft. By 1914, he had created a four-engine aircraft capable of carrying one thousand pound bombs for the Russian Army. Meanwhile, back in the U.S., Congress officially created the Aviation Section within Signal Corps on July 18, 1914. Aircraft were beginning to be used by the Allied forces in the war. By May 1918, Congress saw the importance of aviation; through the Overman Act they formed the "Air Service". This removed aviation assets from the Signal Corps, giving aviators more control over their own destiny. However, just as aviation needed most to increase the research and development of this new technology, the war ended and defense funding was once again severely cut.

As civil aviation boomed in the 1920's and 1930's, Army aviation tried to find itself. In 1926 Congress established the Army Air Corps. The Air Corps spent the next several years concentrating on large bombers; close air support was practically ignored. Military doctrine at the time was that the next war would be fought on the ground and from high in the air, and that air power was best used beyond the range of artillery. Meanwhile, in May 1941, the first sustained flight of a Sikorsky V-300 helicopter took place. This aroused the Air Corps interest in helicopters and on 20 April 1942, Sikorsky delivered the first XR-4 helicopter to Army. The R-4 was the first mass produced military helicopter. They were used for observation, reconnaissance, and medical evacuation missions. An Army R-4B was the first to perform a military rescue behind enemy lines on April 25, 1944 in Burma. Between 1942 through 1946, the Army Air Force had purchased over 300 helicopters. However, combat usage of this unproven technology remained rather limited.

Considerable changes hit the military when on 9 March 1942, Congress established three separate and coequal commands: Army Ground Forces, Army Air Forces, and Army Service Forces. This division of power was in its infancy as WW II raged on. Then in the 1947 the National Defense Act formally established the Air Force. The military chiefs met to decide on their missions. These negotiations resulted in the Army limiting their fixed wing assets to less than five thousand pounds, while the Air Force would provide the necessary close air support. This historic event resulted in the Army developing helicopter fleets to compensate for the loss of its fixed wing support.

The United States entered Korea with nearly the same sad state of readiness that they took into WW II. The services had suffered from neglect because of severe "downsizing" after the war. The Air Force was mainly equipped to fight a nuclear war with heavy bombers. Once the few significant targets were eliminated in Korea, the bombers had little impact. Helicopter use was relegated to search and rescue missions as the Army did their part from the air. As the war raged on, Army H-13 helicopters, first fielded in 1951, were retrofitted with stretchers on their landing skids to transport the growing number of wounded to Mobile Army Surgical Hospitals (MASH). By war's end, over eighteen thousand wounded had been transported by H-13s. The civilian version of the H-19 Chickasaw was the world's first transport helicopter. Built by Sikorsky, the H-19 could carry six litters and one medical attendant during Medevac missions. With seating for twelve, the Chickasaw was also used as a troop transport, utility carrier, and rescue helicopter. The success of the H-13 and H-19 in Korea helped the Army leadership see the importance of the helicopter on the future battlefield.

B. ATTACK HELICOPTERS:

The use of force from the air dates back to the Balloon Corps and its limited attempts to arm aviators. With their growing fleet of large aircraft, the Air Force quickly perfected aerial bombing techniques. The Boeing B-17 "Flying Fortress" ushered in the use of an all around aerial attack with its various crew gun mounts and the ball-turret mounted beneath the huge slow aircraft. Fighter aircraft were developed to help protect the bombers. However, close air support was left largely to the different services and usually heroic individual efforts. Backyard trial and error continued throughout WW I and WW II as ingenious aviators and mechanics attempted to arm their aircraft for battle.

The Army Ground Forces Board at Ft. Bragg, North Carolina, documented the first formal test of an armed helicopter on December 14, 1945. The purpose of the test was to determine if a recoilless rifle could be mounted on a helicopter and fired in flight. Test results show that when fired, the backpressure of the 75mm rifle broke the Plexiglas windscreen and slightly buckled the tail cone of the test aircraft. Due to the lack of an adequate means of sighting the gun, the testing was halted. Helicopter armament was brought to a standstill for the next several years as the fledgling helicopter industry grew. Meanwhile, the Air Force continued to concentrate on fixed wing assets and preparations for nuclear war.

The Army used lessons learned from the Korean conflict to boost their helicopter transport fleet. When the Army entered Vietnam, the need for close air support quickly became a priority. The entire helicopter fleet came under enemy fire; it wasn't long before the need for aerial defense was realized. The Army relied on its aging fleet of CH-21 Shawnee tandem rotor helicopters as flying trucks. Dubbed the "flying banana", this was the first true multi-mission helicopter, utilizing wheels, skis or floats for different terrains. Shawnee was the fourth of a line of tandem rotor helicopters designed by Piasecki. The slow CH-21's were sitting ducks for enemy fire; one was even rumored to be have been brought down with a Viet Cong spear. The CH-21's were soon outfitted with guns in the doorways and on the skids. Several different gun experiments took place in the early 1960's. Some Shawnees were equipped with movable nose guns. The Army even attempted to mount a B-29 Superfortress ball-turret beneath a CH-21, but this experiment was quickly discarded as the forces of the blast damaged the test aircraft. The Shawnee remained the workhorse of the Army through the early years of Vietnam. Use of the CH-21 ended with the arrival of the UH-1 Huey and the CH-47 Chinook on the battlefield.

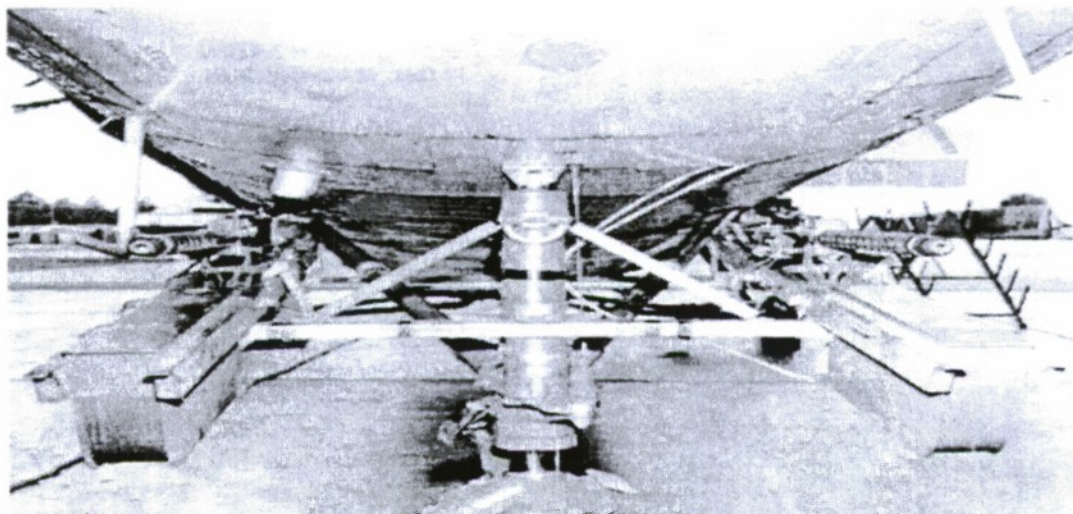


Figure 1. Test of .50 cal Guns on CH-21 Shawnee (1962)

Bell Helicopter's UH-1 Iroquois was a result of an Army proposal request for a general utility helicopter. Bell began development of the prototype in 1955 to meet the Army specification. The "Huey" as it was called after its original model designation, the HU-1, was essentially a stretched Bell model 47 Sioux with room for seven troops or three stretchers in its cargo compartment behind the pilot. As Hueys entered service in Vietnam they were first armed with two door guns.

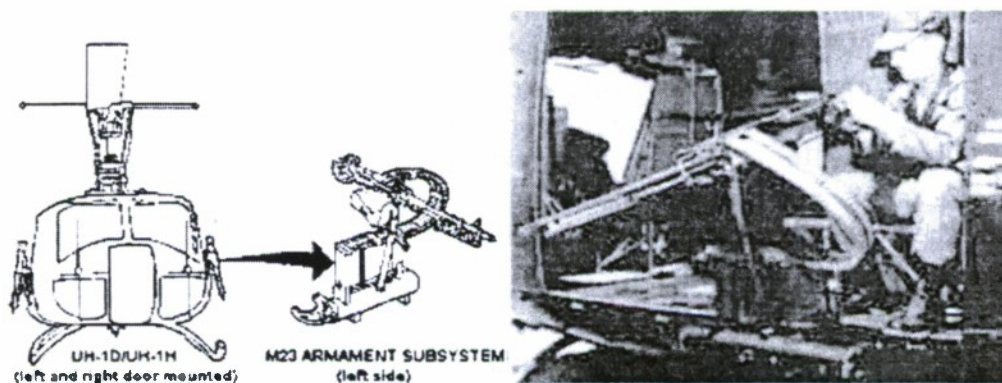


Figure 2. Huey Door Mounted Machine Gun

The CH-47 Chinook tandem rotor helicopter was developed in the late 1950's in order to meet increased demand for an all-weather heavy cargo carrier. The YCH-47A made its initial flight on 21 September 1961 and was fielded to Vietnam in the mid 1960's. In an experimental project, Boeing Vertol equipped four Chinooks with five machine guns, two 20 mm cannons, two rocket launchers and a "chin-mounted" grenade launcher. Designated "Guns-A-Go-Go" these heavily armored aircraft, each with a crew of eight, entered service in late 1965. The aircraft proved highly effective clearing landing zones and in assault missions. Each aircraft was capable of carrying a ton of expendable munitions. However, they were difficult to maintain and following a number of accidents, the effort was terminated in 1967 with the introduction of the AH-1 Cobra.

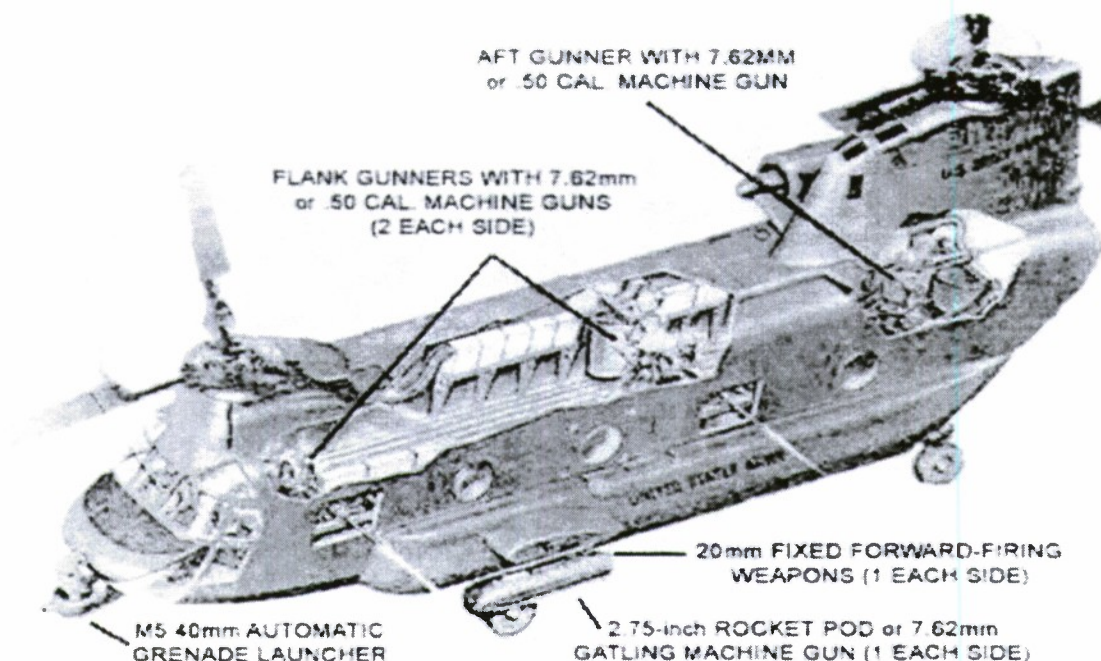


Figure 3. Heavily Armed "Guns-a-Go-Go" Chinook

As the war raged on in Vietnam, the Army realized the need to control its own close air support. In June 1963, the Army issued a request for proposals for the Advanced Aerial Fire Support System (AAFSS). A competition pitted the traditional helicopter builders Sikorsky and Bell versus Lockheed, a newcomer to the helicopter trade but with considerable fixed wing experience. Bell entered a scaled-down version of its Iroquois Warrior. Another competitor was the Sikorsky S-66. The Sikorsky design had a rotorprop tail rotor which could rotate on its axis 90° to act both as an anti-torque rotor or as a pusher, thereby transforming the S-66 into a compound aircraft in cruising flight. The Lockheed AH-56A Cheyenne won the competition.

On May 3, 1967, the first prototype YAH-56 Cheyenne rolled out of the Lockheed facility. The futuristic design had exceeded Army expectations. The Cheyenne had a single rigid four-bladed main rotor and anti-torque tail rotor, and a three-bladed pusher. The radical design of the Cheyenne helped it to reach an astonishing

Figure 4. Cheyenne YAH-56



speed of 256 miles per hour, over twice the top speed of a UH-1. The rigid-rotor Cheyenne, with a crew of two, had a swiveling gunner's station linked to rotating belly and nose turrets, and a laser range-finder tied to a fire control computer. It was armed with a 30mm automatic gun in the belly turret and a 40mm grenade launcher or a 7.62mm Gatling machine gun in the chin-turret, TOW missiles, and 2.75 inch rocket launchers. The turret guns were slaved to the pilot's or copilot's helmet sight, this allowed either to aim and fire by simply turning his head. The age of the attack helicopter had arrived. However, as requirements were added ("requirements creep"), the Cheyenne became even more complex, expensive and worst of all, behind schedule.

The Army had an immediate need for firepower in Vietnam and the top brass were impatient with the slow progress of the Cheyenne. By January 1965, the Army released a proposal request for an interim Attack Helicopter, "escort gunship". Three systems competed for the contract, the Sikorsky Sea King, Kaman Seasprite and Bell Cobra. Bell won the flyoff and by October 1967, the first Cobra missions were flown in Vietnam. As the world's first attack helicopter, the Cobra's mission was direct fire support, armed escort and reconnaissance. It was armed with a 40 mm grenade launcher, 7.62 mm "minigun" and 2.75-inch rocket launchers. The Viet Cong named the Cobra "Whispering Death".



Figure 5. AH-1 Cobra Gun Ship

Stateside attention turned once again to the struggling Cheyenne program. Rollout of Lockheed's first prototype YAH-56 Cheyenne took place on May 3, 1967. The Air Force saw the Cheyenne as a threat to its close air support anti-tank mission. Secretary of the Air Force Harold Brown ordered the development of the A-10 Warthog to meet that need. As the Cheyenne continued to have technical problems, the Cobra was proving itself in battle. The Army soon realized that they would not win a turf war with the Air Force. With the A-10 project in full swing, the Army decided that they wanted a smaller, more agile Advanced Attack Helicopter (AAH) with a less complicated fire control and navigation system. The Cheyenne contract was terminated in May 1969. Through this period, the Army continued to desire fixed-wing close air support (CAS) from the Air Force. To that end, it was, relatively easy for the two services to agree that the attack helicopter did not perform CAS. Instead, it was an extension of organic firepower, and the Air Force would continue to provide CAS with fixed-wing aircraft. The two services agreed to consider the two types of aircraft as complementary rather than duplicative. Since that time, there have been no serious disagreements over aviation missions and functions between the Army and the Air Force. The new helicopter's

mission would eventually be filled by the AH-64 Apache Attack Helicopter.

C. APACHE ATTACK HELICOPTER

The McDonnell Douglas (formally Hughes) AH-64 Apache is a twin-engine rotary wing aircraft, designed as a stable, manned aerial weapon system. With its two pilots and sophisticated computers, the Apache is capable of defeating a wide range of targets, including armored vehicles. It is capable of performing missions, day or night in adverse weather conditions. Combined with the integrated Target Acquisition Designation Sight / Pilot Night Vision Sensor (TADS/PNVS), the platform provides day and night acquisition and designation of targets and hand-off capabilities in support of Hellfire and other guided munitions. Aircraft armament includes the Hellfire anti-tank missile system, 30mm automatic chain gun and 2.75" rockets. The platform has a full range of aircraft survivability equipment with the ability to withstand hits from rounds up to 23mm in critical areas. Powered by two General Electric gas turbine engines, the Apache can cruise at an airspeed of 145 mph with a flight endurance of over three hours. The AH-64 can be carried in the C-5, C141 and C-17 transport aircraft. The Apache Attack Helicopter contributes a highly mobile and effective firepower asset to the anti-armor capability of the Army.



Figure 5. Apache AH-64

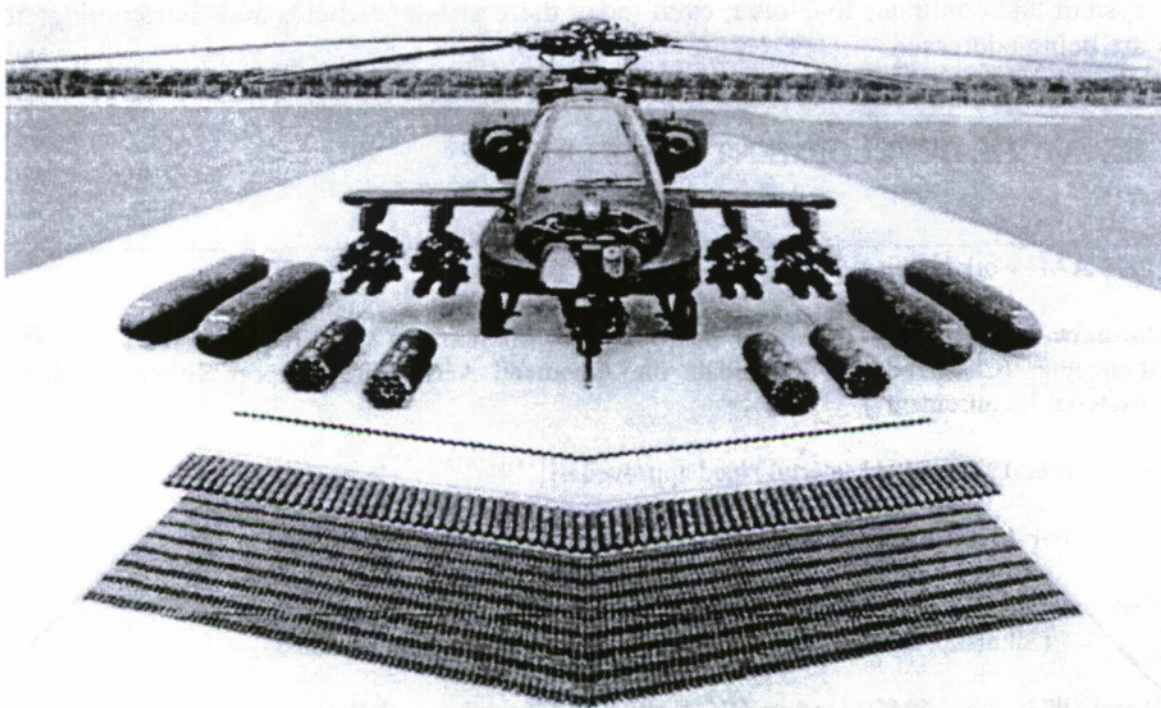


Figure 6. Apache Armaments

D. DESERT STORM (REVISITED):

In the early morning of 17 January 1991, an Army aviator fired the first shot of Operation Desert Storm from an Apache helicopter. Within a few minutes, two teams of Apaches totally destroyed two Iraqi air defense radar stations, paving way for the air war over Iraq.

During the 100-hour ground war, Army attack helicopters played their most decisive role ever in combat. Whatever doubts remained regarding combat effectiveness of attack helicopters were quickly dispelled. In addition to the attack role, helicopters were used for air assault, reconnaissance, transportation, combat search and rescue, and observation. Dozens of aviation units and several hundred helicopters of all types took part in the Gulf War.

Helicopters, as well as most other types of equipment, were adversely affected by sand and other environmental conditions; however, methods were devised to control the damage and to maintain a high rate of combat readiness. Operation Desert Storm was the first major military operation conducted on a largely electronic battlefield. Army aviation amply demonstrated its effectiveness in this environment and also proved again that it could "own the night" by carrying out many of its combat operations during darkness.

The reason that the Apache strike force team included four Air Force MH-53J Pave Low helicopters to help start the Gulf War was that the Apaches needed to follow the Pave Lows across the desert due to the Apache's lack of adequate navigation equipment capable of traversing the flat, featureless Mid Eastern terrain. The Apache is a

system that continues to evolve; even today there are deficiencies and shortcomings that are being addressed.

E. APACHE DEVELOPMENT SUMMARIZED:

1970 AAH work begun

January – August 1972: Marks Board formed, mission: To study requirements for an attack helicopter (Chartered to: "Revalidate the Advanced Aerial Fire Support System Qualitative Material Requirement")

September 1972: AAH Material Need approved

November 1972: AAH RFP released

February 1973: RFP responded to by 5 companies
(Sikorsky, Boeing-Vertol, Bell Helicopter, Hughes, and Lockheed)

April 1973: AAH PMO stood-up (BG Samuel G. Cockerham, 1st PM)

June 1973: Down select to competitive development with Hughes and Bell Helicopter

September 1975: First flight, Bell's YAH-63A & Hughes' YAH-64A

April 1976: New AAH PM (MG Edward M. Browne, April 1976 – December 1982)

June 1976: Prototypes delivered to Army for flyoff

December 10, 1976: Down select to Hughes YAH-64A

June 1981: Operational Test (OT II) @ Hunter Liggett (Ft. Ord, CA)

FY 1982: Congress approves LRIP, \$444.5 M Contract for 11 aircraft

November 1982: Hughes completes \$300 M AAH production facility in Mesa, AZ

November 1982: \$106 Million low rate production contract for 48 aircraft

September 30, 1983: First production aircraft complete

December 30, 1983: Hughes Helicopter Company sold to McDonnell Douglas Corp

Spring 1984: \$841 Million production contract for 112 aircraft

Table 1. APACHE Development Timeline

As previously noted, a sense of urgency came over the Army leadership following the rise of the Air Force A-10 program and the demise of the Army's Cheyenne program. Combat development representatives of the troops in the field were on board early in the

program and supported the program as it evolved. Once the Apache PM office was established in April 1973, the PM kept in close contact with Training and Doctrine Command (TRADOC) and user representatives during the remaining phases of the project. That close working relationship helped user support to grow as the program progressed toward production. As is usual with the military rotation cycle, there were several changes in key user personnel during the program. Top leadership helped make sure that these changes occurred early in development and between development and the transition to production. Keeping key user personnel on board through major milestones helped to minimize the effect of these inevitable changes. Table 1 summarizes the program.

Initially, clear requirements helped to keep the program on course. The Advanced Attack Helicopter (AAH) Mission Needs Statement (MNS) and operational requirements were the result of a revalidation of the Advanced Aerial Fire Support System qualitative material requirements that spawned the Cheyenne program. The new mission needs statement (MNS) stipulated that the AAH would be in production by 1978. This put the program on a tight schedule from the start. There were several new technologies on the horizon that could not be integrated in time to meet the fielding date; the Hellfire missile contained such technology. The PM worked closely with the user community to build a program that would meet their needs (e.g., being able to fight a cold war battle in all weather conditions) and still meet the first unit equipped (FUE) timeline.

It was said that the PM "ruled with an iron fist" as the system progressed through development. This caused great consternation throughout the technical community, but kept the program on course. Significant effort was spent on controlling the problem of requirements creep. Although there were changes in system requirements as the program evolved, such as the laser guided Hellfire missile added in February 1976, the close working relationship between the user and PM office helped foster a mutual trust. Significant requirement changes were kept to a minimum as the program progressed through development and on into production. Many requirement changes were addressed as preplanned product improvements after the system transitioned to production.

In spite of this restraint, the project significantly exceeded initial budget estimates. Prior to approval of a large program by the Defense Acquisition Board (DAB), the Office of the Secretary of Defense has the Cost Analysis Improvement Group (CAIG) provide a per unit cost estimate. The CAIG is chartered to provide an independent review of life-cycle cost estimates and to determine if additional analysis is required. The CAIG's flyaway unit cost estimate for the Apache was \$1.7 million in fiscal 1972 dollars

The program was slowed down, due to funding cuts. As the Carter administration took the reins of Government in Washington in 1976, the Apache flyaway cost had significantly increased. The new Secretary of Defense in the Carter Administration, Harold Brown, formerly the Secretary of the Air Force, was specifically the one who pushed for the A-10 that helped kill the Cheyenne program. Brown cut the Apache budget by one half on the second week of the Carter Presidency. To make up for the funding shortfall, the development program was stretched an additional ten months.

There was often uncertainty about the future of project funding during the system development stage. Flyaway costs hit \$6.4 million in FY 1977 dollars. The 1978 DoD appropriations bill contained only half the requested funding for the Apache; the program was almost cancelled. Despite the cuts the program pressed on and the platform proved itself during subsequent user testing. The high marks that the Apache received from the test community helped greatly when the program moved for production approval. In 1982, Congress authorized \$444.5 million for low rate initial production

F. CRITICAL TECHNOLOGIES:

AAH systems planning and pre-development work started in 1970, soon after the Cheyenne contract was terminated. Government interviewees stated that they never even changed offices; they went from working Cheyenne one day, to the AAH program the next. As noted earlier, the Cheyenne had tried to push too far beyond the current state-of-art technology; this caused serious cost over runs and schedule slips. The new AAH program quickly set out to distance itself from the Cheyenne. Technology maturity was a key factor in determining the capabilities needed for the new aircraft.

The Apache program wanted to integrate several new technologies onto its platform. These were highly sophisticated subsystems from as many as eight different development projects, along with a number of subsystems developed by the prime contractor and other suppliers. Among these technologies, three were considered to be central to the success of the Apache system, that is, the program would have failed if these technologies were not available for production. The first critical technology was the Target Acquisition Designation System/Pilot Night Vision System (TADS/PNVs), used to acquire targets in all battlefield conditions. The second was the avionics computer systems; that is, the processors used to control the flow of information on the platform. The third critical technology addressed is the avionics used to control aircraft flight.

The (pre-development) systems planning stage of the program started with a revalidation of the requirements. In fact, government interviewees noted that the definition of the Advanced Attack Helicopter was constrained by what the Department of the Army thought the helicopter industry was capable of producing. Great care was taken to assure that the technologies were feasible prior to sending requests for proposals to industry. The concept for the system itself was rather immature; the technology concept and application had been formulated. However, the application was speculative and there was no proof or detailed analysis to support the assumptions. Examples were still limited to paper studies. At the subsystem level, the TADS/PNVs and computer systems needed the most work as they were both relatively immature. Some parts of these systems were taken off the critical path at the beginning of development, only to be added later as they matured. The avionics system was relatively mature. Avionics system and subsystem models and prototypes were demonstrated in a relevant environment. Representative models and prototype systems, which were well beyond the breadboard stage, had been tested in high fidelity laboratory environments and in simulated operational environment.

The Army labs at Communications and Electronics Command (CECOM), Missile Command (MICOM, for the TADS), the Night Vision Lab and TRADOC accomplished

the primary work performed in the period from system planning to development with oversight from the Government program management team remaining from Cheyenne. Much of the behind the scenes effort was done by competing contractors vying for the replacement of the Lockheed Cheyenne. Five companies submitted proposals for the AAH. They were: Sikorsky, Boeing-Vertol, Bell Helicopter, Hughes, and Lockheed.

The development program started in April 1973, as the AAH PMO was first stood-up; BG Samuel G. Cockerham was the first PM. The first task of the new PMO was to down-select the proposals received towards the end of the systems planning stage. Hughes and Bell Helicopter were selected for competitive development. Each would build prototypes that would compete in a "winner take all" fly-off for the production contract. The new PMO had a lot of work to do in a very short period of time.

At the start of development, the overall system had progressed to the point that components and/or breadboard validation had been done in a relevant environment. Fidelity of breadboard technology was significantly increased. Basic components were integrated with reasonably realistic supporting elements so the technology could be tested in a simulated environment. Examples included "high fidelity" laboratory integration of components. The production maturity for the system at this point was sufficient to support the fabrication of prototypes with tools and processes used for producing very low quantities. During development, the Army labs at CECOM were involved with engineering support and requirements interpretation. However, in the case of the TADS/PNVs, the Night Vision and Electro-Optic Lab, together with the MICOM's Guidance and Control Lab provided much of the expertise in this new technology.

The three critical technologies were in different levels of readiness at development start. Suppliers were quickly trying to bring their subsystems up to maturity levels that would support integration into the system. The TADS/PNVs and computer systems had been through component and/or breadboard validation in a lab environment. This was still relatively "low fidelity" compared to the eventual system. The avionics systems were much more advanced, as many had been integrated into other platforms to some degree. Avionics prototypes had been demonstrated in an operational environment by use of test bed aircraft. These prototypes were near or at a planned operational configuration.

Apache was transitioned to production in April 1982. At that point, a producible system prototype had been demonstrated in an operational environment. The prototype closely represented the planned operational system and was produced in low quantities with tools and processes that were planned to be used in the production systems. Testing procedures for components and subsystems were established. The two competing prime contractors' science and technology organizations accomplished the primary work in the period from development to this point. Other organizations that had been involved in the period included active support from component suppliers and the CECOM, MICOM and Night Vision Labs. These Army labs provided engineering support, simulation and testing

After the system was accepted and was in the transition to production phase, significant changes in the designs and processes were later required before the system was taken into full production. Each of the critical technologies was used as planned in

the final system. After the system was actually in production, significant changes in designs and processes were also required. However, the system as it was implemented met or exceeded the project's technical goals.

Interviewees noted that the system experienced some problems in the field under operational conditions in Desert Storm. Sand and dust played a significant role in many of the problems. These problems may well have resulted from the requirements not reflecting the true field environment.

G: TEST STRATEGY

The test strategy for the Apache was divided into several phases. The initial testing for Phase I of the program involved two competing contractor designs. As noted earlier, Hughes Helicopter and Bell Helicopters were each awarded a contract in June of 1973 to proceed into development. The designs competed in a fly-off. The first flight for both aircraft occurred in September 1975, followed by six months of contractor testing. Prototype aircraft were delivered to the Army in June 1976 for evaluation. The Hughes design won the competition and was awarded the phase II contract in December 1976.

The Apache program entered testing with the failure of the Cheyenne program fresh on everyone's mind. A failure modes and effects analysis was done on the system. This analysis was performed early enough for the results to be used to establish the test plan. The failure analysis also helped establish the critical test parameters for both the system and key components.

Several organizations were involved in testing the various components that were about to be integrated onto the Apache. Testing and simulations were performed first to see if the individual components of the system worked. The prime contractor, component suppliers and Army labs at both CECOM (Avionics) and MICOM (TADS), and the Night Vision Lab (TADS/PNVS) performed the bulk of this testing with oversight from the PMO.

The integrated components were tested working together in a controlled setting. This testing takes the most time, as problems are found, fixed and the integrated assembly is retested. To reduce the cost of retest, simulations were also performed with the components working together in a controlled setting. The prime contractor, suppliers and to a limited degree, Army labs performed these simulations. A hardware-in-the-loop type systems integration simulation laboratory was used to see if the individual components of the system worked and to see if integrated components worked in a controlled setting.

As the system evolved, testing was performed on the components working together in a realistic setting. The organizations that performed this testing included the prime, suppliers and Army labs. Once all the bugs were worked out, the system was turned over to the Government operational testers for their independent evaluations. The Apache operational testing was performed by Army pilots and occurred from June to August 1981 at Ft. Hunter Liggett. The Program Management Office kept a constant vigil over the testing. To accomplish this, the Apache PMO established a field office at the test area. This office kept the PM aware of what was going on at the test site, quickly resolved problems and facilitated the flow of spare parts. This relationship helped the

Apache program stay on course and get through operational testing on schedule and within budget. The system soon advanced to Acquisition Milestone III and approval to enter into production.

There were several environmental issues found when the Apaches were first deployed. When they fought in a jungle, water intrusion was a major problem. During the Gulf War, the fine sand particles caused new challenges.

H: APPROACH TO DEVELOPMENT/PROCESSES:

The project was not set up with a cross-functional IPT, that is, a project team drawn from different parts of the organization with most of the skills needed for the development. (The current trend in project organization is to form cross-functional integrated product teams (IPT). This is used to assure that all aspects of process integration are addressed. The Apache program development occurred during the 1970's, about 20 years prior to the use of the formal IPT process.) Instead the project team had smaller technical cells, each concentrating their own specific piece of the program. The contractor's program management office had oversight of the cells and was responsible for pulling all of the pieces together.

Nearly two thirds of the people on the contractor's team were new employees and thus had never even worked with others at Hughes until the Apache development. Attack helicopter development was new to Hughes Helicopters. During the development stage of the project, the contractor had just over one third of the people on the team collocated in the same building. Few were collocated very close together, that is, on the same floor of a building within a one-minute walk. However, most of the requisite key technical skills were well represented on the team itself. Key members stayed with the team through pre-production planning and testing.

The team leaders were skillful at getting necessary resources. Team leaders were fairly effective at resolving technical disagreements during development. Turnover in team membership was minimized. Team leaders sometimes needed management help to resolve project team disagreements. Usually the team knew right away where to get necessary outside help on those occasions when it was needed.

Formal reviews were conducted at key decision points. The primary goal of these meetings was to pass high-level data among the key players and the Government. These management project reviews were only minimally constructive. These reviews tended to take away from the flow of the project as personnel spent extra time with the rigid documentation requirements. Reviews for major weapon systems tend to attract large numbers of participants. Meetings were sometimes unwieldy, frustrating and non-productive.

Later in development team members started to go to the shop floor to meet about related production processes. Planning meetings were held that included both design and production people. Physical prototypes were passed around during these joint discussions. Suppliers provided comments and suggestions on design choices as team members showed and discussed physical models of new components with suppliers. Design and production technicians explored choices together with computational models

and analytical tools. They used test articles or pre-production hardware to discuss and examine problem. Just prior to the production transition phase, production representatives participated regularly in development meetings. Team members also began to meet regularly with production personnel out on the shop floor. Technical professionals from production started to have unscheduled, informal joint conversations about the project with design personnel. At that point, analytic engineering tools were being used jointly by design and production. Prototypes and parts were being used regularly in joint discussions.

As the program was readied for production, it became evident that logistics skills were lacking from the program. Realizing the deficiencies, a cross-functional working arrangement was key for the transition into production. Logistics is traditionally pushed off until the end of the program. This can have serious, long lasting effects on the user if not addressed. Although the team leader was technically competent, he had little experience in both design and production. By the time the program entered production, a form of IPT approach was used to resolve problems. Project results benefited from the team's best ideas.

I: KEY ISSUE FACED BY PROJECT MANAGER:

Control of the production project was the biggest fundamental problem the PM had to deal with in managing the overall program. Problems of control were basically the external environment, i.e., the sheer number of agencies that were to be contended with on a regular basis under the "team" approach. Like the internal organization, each had its own special interest area(s) and each had some level of input and "veto" power. As an example, meetings were inordinately large and therefore difficult to control. Decisions that should have been made instantly were negotiated to death leaving cost and schedule impacts to be resolved.

The PM controlled and dictated the R&D Program. Had he not dictated the R&D program there would not be an AAH today. An example of this control was cited by one of the Government interviewees. This occurred shortly after the initial production contract was awarded to Hughes. At that time, Hughes Helicopters was headquartered in Culver City, CA. Hughes management was looking for a site in the traditional California manufacturing corridor to build a production facility. Fearing high labor costs due to greater competition for skilled people, the Apache PM, General Browne ordered a cost-analysis study of the area. It found that if Hughes located in this high cost area, the personnel and manufacturing costs could reduce the total Apache buy nearly in half. With strong urging from Army and DoD leadership, and a few political incentives, Hughes chose Mesa, AZ to build their \$300 million facility that would eventually employ two thousand workers.

J: LESSONS LEARNED:

User Representatives:

The Apache program survived in a difficult political climate because the Program Manager and user representative worked closely together. It is really important to get the user representatives on board early and it is most beneficial if the PM's relationship extends to form a close working relationship with the user community. Good user support is crucial throughout the program, and including the user in all major reviews can reinforce it. This relationship must be based on trust.

Requirements:

The Apache program manager kept requirements under control by working together with the user. Requirements creep must be managed but can be kept in check if stakeholders have a clear understanding of the evolutionary path of the system. With most program developments, there are a lot of potential contractors who will try to sell their systems to the user. The PM must be ready to manage the technological side of the program to help the user sort through the "smoke and mirrors" that marketeers for these organizations use to hype their wares.

Funding:

The Apache program experienced several funding fluctuations; the PM was ready and dealt with each as it occurred. Funding stability is an issue in any large program spread out over many years. People are constantly out to get your money. You need to be on the lookout for internal suitors from your own service, those from other services and outside forces from Congress. The slightest schedule slip or problem in a program will bring its competitors to its doorstep ready to take funds that it no longer can execute.

Technology:

The Apache program had several changes in technology throughout development. They were able to track technology readiness in key areas and mitigate risk by moving certain enhancements off the critical path. Technology readiness also played a vital role when adding capabilities such as the Hellfire missile. The technology readiness status of advanced systems must be clearly articulated to the user by the Government technical experts to assure that the users requirements can be met. Technology readiness should be evaluated throughout the program to assure that the system can stay on schedule. Shortfalls in technology readiness can significantly impact the program.

Teaming:

The Apache program was developed before the advent of formal integrated product teams (IPT). However, a form of IPT was used for early production. Until then, the program was put together in smaller pieces, with teams concentrating solely on their individual area. This caused delays in the schedule when key components were not ready for system level testing. The IPT process should be utilized to ensure that all aspects of the project are addressed. Good leadership and a clear vision are keys to a successful IPT. Membership must be addressed early so that decision makers are consistently present.

Testing:

The Apache program manager made test readiness a primary goal. The test team was properly staffed with the proper resources at their disposal. The test plan is an important document that helps lay out the program schedule. By performing a Failure Modes Effects and Criticality Analysis (FMECA) early, the Apache PM was able to use the results to help build the test plan. This information also feeds into the Test Evaluation Master Plan (TEMP) required for Milestone reviews. Testing on the Apache followed a traditional approach of test-fix-test. The system had clear transitions from development to operational testing. The test plan was modified as required by funding and schedule slips. It's the program manager's job to make sure that the system is ready for test. In the end, the fact that the system was able to demonstrate its operational capability in real world environments helped save the program from cancellation.

Several operational problems were noted by the interviewees. It's impractical to test out every potential operational scenario. Unforeseen problems and systems deficiencies are found nearly every time a new system is fielded.

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B
ATACMS

Army Tactical Missile System (ATACMS)

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ATACMS – Mr. “Reach out and touch somebody”

“The soldiers of Desert Storm referred to ATACMS as AT&T,...for “Reach out and touch somebody”¹

Introduction

This case study covers the development of the Army Tactical Missile System (ATACMS). The early exploration and development work leading up to the Engineering and Manufacturing Development (EMD) or Full Scale Development (FSD) phase of the program is covered to capture essential technology growth that preceded the formal start of the ATACMS program.

Revolutionary doctrinal shifts and emerging technologies brought about the required mix of the proper ingredients for a successful acquisition program. The exploratory and planning phases cover work in Army missile laboratories and within the Defense Advanced Research Projects Agency (DARPA). Two major technology demonstration programs explored many of the technologies and concepts that develop into the ATACMS system. However, the overall development history also includes two early attempts to formulate an acquisition program for a missile system of this type.

The FSD phase will be covered in detail, exploring two technologies that were critical to the success of the ATACMS program. The maturity of the three technologies will be tracked based upon the assessment of government and contractor program managers and others involved in the process. Several critical issues experienced during the FSD phase will also be explored. These critical issues serve as examples of how the program and the program managers for the government and the prime contractor reacted to difficult issues and events that could have impacted the successful development of the system.

Prelude to ATACMS

Doctrinal Transformation

The doctrinal transformation near the end of the Cold War and the support of the Training and Doctrine Command (TRADOC) system manager (TSM) is an essential aspect of this development program. The transition in thought that led the Army to create and endorse the emergence of the AirLand Battle concept occurred at the same time as the beginning technology demonstrations are taking shape in Army laboratories. The doctrinal shift centered around the rejection of the previous belief that early use of nuclear retaliation would be essential to repel an aggressive move by the Warsaw Pact (WP) in Europe. This belief was held because of the numerical superiority of the WP forces. However, following the victory of the numerically inferior forces in Israel in the Yom Kippur (Arab-Israeli) war in 1973, the seeds of

change started to germinate. The words of Gen. Donn Starry summarize nicely the major new and radical principle that is at the heart of the AirLand Battle Doctrine.

"I realized that we had to delay and disrupt, deep into the enemy's battle area. The orderly advance of their follow-on echelon would have to be stopped. We wouldn't have to destroy them. It would be nice if we could. But all we really had to do was prevent them from getting to the battle, so they couldn't overwhelm the defenders."²

The AirLand battle as doctrine was molded by a number of people while it was being created and by still many others to the current day. However, several individuals and their ideas and beliefs influenced the doctrine more than others. Gen. Starry and Gen. Don Morelli³ are the primary people who are given credit with moving the doctrine from point papers into an approved formal doctrine. However, some parts of this doctrine draw heavily from the works of Col. John A. Boyd⁴. The overall concept of his Observe, Orient, Decide, Act (OODA) loop is a part of the definitions which form the main tenets of the AirLand battle. These tenets are; **Initiative** – setting or changing the terms of battle by action, **Agility** – the ability of friendly forces to act faster than the enemy, **Depth** – Extension of operations in space, time and resources, **Synchronization** – arrangement of battlefield activities in time, space and purpose to produce maximized combat power at the decisive point. Depth is described as "engagement of enemy units not yet in contact to disrupt the enemy timetable, complicate command and control and frustrate his plans, thus weakening his grasp on the initiative"⁵ The emergence of this doctrine and the ramifications on both the Army and the Air Force helped to shape almost all of the acquisition programs during the next twenty years.

The AirLand battle doctrine helps to provide the structural foundation for the program that becomes ATACMS. Airland battle as discussed emerged as Army doctrine and it had a counterpart in the North Atlantic Treaty Organization (NATO). In NATO, a broad mission concept emerged and contained a subset called, Follow on Forces Attack (FOFA). Starry discussed and summarized his message for AirLand battle with these four elements;

- Attacking deep is essential to winning
- Attacking deep and the close-fight are inseparable
- The extended battlefield concept is the keystone of force modernization
- We can begin today to practice, learn and refine the extended battlefield concept.⁶

Early Technology Demonstrations

SIG-D

SIG-D is the acronym for the Simplified Inertial Guidance Demonstrator program. This program was sponsored and guided by the Army Missile Research and Development Command (MICOM) and the Army Missile

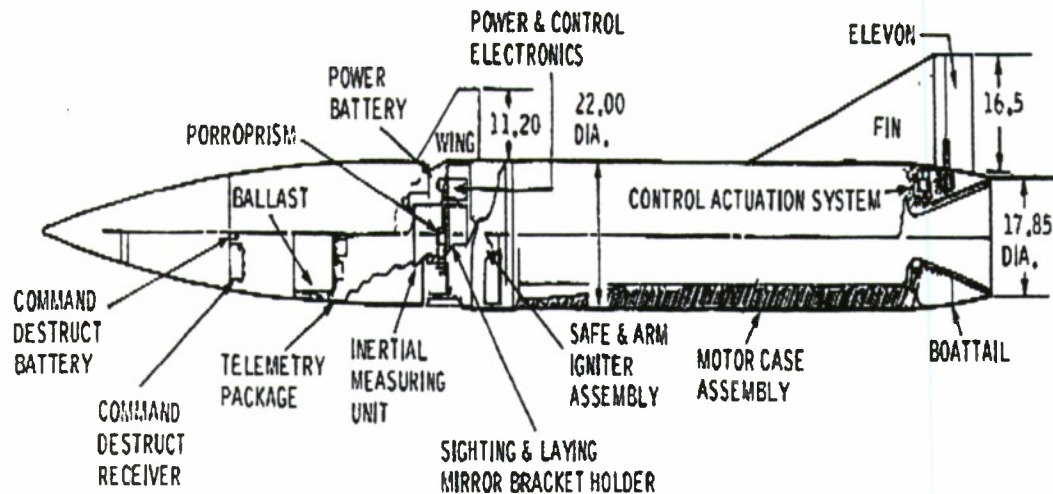


Figure 1 – The T-22 Missile used for SIG-D and later Assault Breaker (©AW&ST,1980)

Laboratory and was conducted to demonstrate the emerging technologies in guidance, propulsion and control.⁷ Three test missiles were fired based upon an updated propulsion system moving away from the Lance liquid fueled engines toward a solid rocket motor that was built from modified Lance components. These motors followed from experience gained on the "Greener Pastures" program that had been terminated and the motors put in storage.⁸ The SIG-D missiles were assembled with motors that utilized Polybutadiene Ammonium Nitrate (PAN) propellant because it was low risk and the main purpose was to prove out the guidance package.⁹ Figure 1¹⁰ shows the layout of the missile that had the exact diameter of the existing Lance systems and was dubbed T-22. The SIG-D missile tests were also used to explore the use of simplified inertial guidance systems, from which the program derives its name.



Figure 2 – One of three SIG-D flight tests

This guidance system used a Honeywell H-700 digital ring-laser-gyro (RLG). The program also explored pneumatic and hydraulic options for the control actuation system (CAS), drawing on technology that had previously only been utilized in small missile applications.

This program is important because it allowed the eventual prime contractor to test and integrate several of the emerging potential technologies into a demonstration missile and collect data to support the simulation efforts that were underway to support both Lance follow on efforts and the ongoing Assault Breaker efforts. It is also important because the data and knowledge gained in SIG-D could be utilized in detailed simulations being created to design and optimize this type of system. These simulations and a large number of critical steps in the design and assembly process were conducted in the Army Missile Laboratory.

The three tests during the SIG-D program provided invaluable data to support the guidance technique and the use of the RLG. An October 1980 issue of Aviation Week & Space Technology issues shows one of the SIG-D test impacts with the missile missing the target stake by only one missile length. The accuracy of the first SIG-D was also reported for a 64 kilometer flight to be within 25 meters of the target aim point.¹¹ This accuracy is not only suitable for submunition application but also for dispersion of conventional bomblets. Interestingly, it is also accurate enough to engage many types of targets without the reliance on a target update. The SIG-D program provided for testing of key elements and integration into a workable prototype that not only achieved success in meeting the objectives of the SIG-D program, but allowed for the development of a key piece of the Assault Breaker testing and architecture. Figure 2 shows the launch of one of the test missiles.¹²

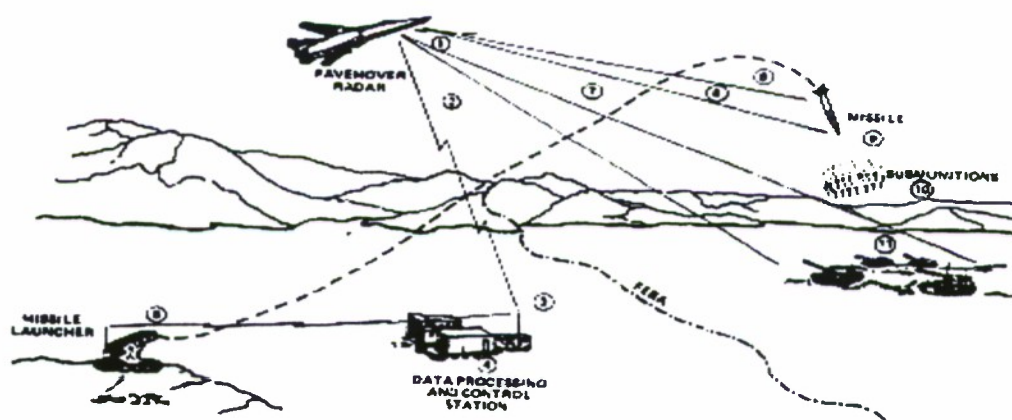


Figure 3 – Assault Breaker: Ground-launched version

Assault Breaker

The previous discussion reviewed the concept of FOFA and AirLand Battle in a generic sense. However, before being seriously entertained by NATO and DOD, several innovative studies and efforts explored key elements and ideas necessary to move this approach forward. The previously mentioned DSB summer study in 1976, started the ball rolling with a review of available technologies to improve conventional forces. In 1978, the U.S. Defense Advanced Research Projects Agency (DARPA) started the technology demonstration program dubbed "Assault Breaker". This program called for weapons to attack enemy formations moving up to the forward edge of the battle area.¹³ DARPA combined several emerging technologies and concepts into a "system of systems" to attack and kill multiple mobile hard targets at standoff ranges with a single delivery system. Figure 3¹⁴ shows an overview of the system concept. The effort not only sought to revolutionize the attack of large armor movements but also the development timeline by briefing interested parties in early April of 1978 and receiving proposals in early May. Continuing the rapid pace, the evaluation activity concluded a mere 12 weeks later with selection of the various teams for each of the key technology requirements.¹⁵ As the discussion of the Assault Breaker effort will make clear, DARPA pursued a rapid-paced, aggressive schedule to demonstrate the concepts and technologies required for attacking armor and other high value targets, with conventional means(non-nuclear) at extreme ranges.

Technologies explored included Synthetic Aperture Radar (SAR) with Moving Target Indication (MTI) capability (e.g. PaveMover), intelligence fusion (beta project) and terminally guided submunitions (TGSM). For this system concept to work a missile "bus" would have to carry the TGSMs to a basket over the target array or arrays. The basic building blocks for the TGSMs, the missile bus, and advances in SAR technologies were advancing in the basic and applied research efforts of both Army and Air Force research laboratories. The concept shown in Figure 3 uses many systems in a complex sequence to achieve the results intended. The first step is for an airborne radar to orbit behind the forward edge of the battle area and search a designated area with the Pave Mover system (1). The data is then transmitted to a ground station (2) to allow for targets to be analyzed and designated (3) and for a battlefield commander to decide the priority of each designated target.(4) A missile is launched at the target and tracked by the radar while the radar still follows the position of the intended target(5) allowing the missile to fly toward the designated dispense point for its payload(6). In the case of moving targets the radar updates its data(7) and sends an update to the missile in flight(8). At the dispense point the missile releases the payload of submunitions(9). In the endgame, the submunitions activate and track (10) and target autonomously maneuver to a position to destroy the target with a conventional warhead.(11).¹⁶

T-16:

The T-16 was based upon the Patriot missile and used the same solid fuel rocket motor. The guidance system was comprised of a high quality inertial navigation

system (INS). For stationary targets the INS guided the missile all the way to the intended target. However, for moving targets a guidance update was required from the Pave Mover radar system. This allowed for course correction based upon target motion and small accumulating guidance errors. The guidance system of the T-16 included a stellar inertial system that provides midcourse guidance by utilizing a star-fix update. The star INS used a two gimbal configuration to focus energy from the selected star onto a 50 element square scanning array¹⁷. Several errors are corrected or improved using this star fix. They include azimuth errors and both updates for altitude and velocity errors.

T-22:

The T-22 was essentially a variation of the missile used in the demonstration program pursued by the Army Missile Laboratory to test emerging guidance technologies. The details of the elements of this missile have been covered in the section on SIG-D. The T-22 propellant was changed to match the propellant utilized in the Vought Multiple Launch Rocket System (MLRS).¹⁸ The missile, designated T-22 during SIG-D, utilized a low cost Hydroxy-terminated polybutadiene (HTPB)¹⁹ propellant. The basic layout and guidance package was the same as that for the SIG-D program. Six test flights were planned with four fully executed using the T-22 configuration. Several of the tests were planned to utilize live submunitions which were under a parallel development effort. Towards the end of the program cost limitations curtailed several planned tests. The T-22 utilized in the test phase of Assault Breaker allowed for a guidance update to be received from the airborne sensor platforms.

By the end of 1982, with the 14 flight tests complete, the question of transition to a full scale engineering development effort became the focus of the Office of the Secretary of Defense (OSD), DARPA, and the Army/Air Force. By many accounts

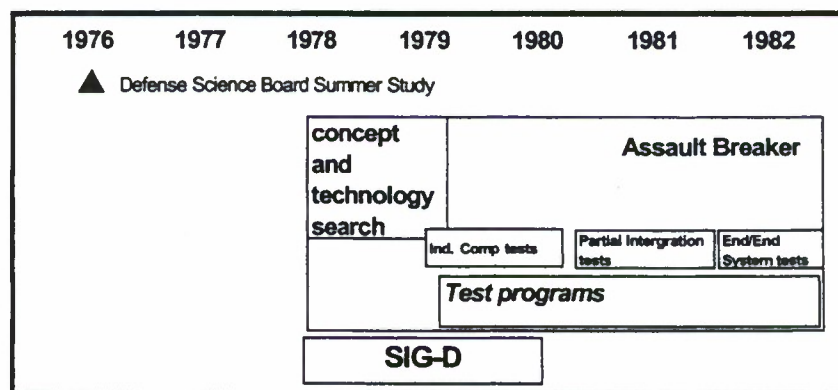


Figure 4 – Demonstration program timelines

the concept demonstrations carried out under this program demonstrated the ability of each of the components of the overall system to progress to the next step of engineering development. However, the transition of this concept to fully funded programs and to the eventual Army efforts that create ATACMS was a complex and intriguing mix of competing requirements, interactions between competing forces in each service and between the services, and the changing world threat environment.

Early Acquisition Programs

CSWS & JTACMS

This section will cover the early efforts at defining requirements by both the Air Force and the Army and the eventual handoff to a Project office that could oversee the program to deployment.

The early efforts begin with the termination of the Lance Project Office in March of 1980. A follow on effort, named the Corps Support Weapon System (CSWS), focused on the nuclear role of Lance but had provisions for enhanced chemical/biological elements. By March of 1981, with growing concern on the part of DOD that two services were attempting to develop overlapping capability and too many similar weapons, the CSWS effort was redirected into then MICOM's Army Missile Laboratory, System Development Office. About the same time the new office assumed a role in the Assault Breaker effort and brought the management of both efforts together.²⁰ Figure 5 depicts the timeline of the efforts that can be seen in hindsight to be the concept exploration and demonstration phases related to ATACMS. The Assault Breaker and SIG-D efforts have been reviewed and the developments of several technologies and system concepts have been explored and demonstrated which showed clearly the feasibility of the concept for conventional attack of massed armor. The CSWS effort should be viewed as the Army attempt to meet their need for a Lance replacement with an expanded capability set. It also had the goal of meeting the Lance missions with equipment that was easier to maintain and utilized less manpower resources. This concept included scatterable mines, terminally guided submunitions and submissiles, chemical/biological and tactical nuclear warheads. Indeed, the early desired range would have been more than 200 kilometers.²¹ Also, with the CSWS, the Army had a system concept under review and therefore had a mechanism to support the Assault Breaker testing during this timeframe. It is important to remember that the CSWS program began just before the doctrinal changes that were discussed at the beginning of the paper. As the world was changing rapidly in this time period, so was the doctrine and therefore the material development needs and requirements of all of the services.

Early Requirements

In mid 1982, DOD directed the Air Force and the Army to combine efforts and produce a common missile system. This effort combined the Air Force's Conventional Standoff Weapon (CSW) program and the Army's CSWS to form a Joint Project Office. After a year of negotiations and planning, the JTACMS Joint Project Office was established in March of 1983. Col. James Lincoln became the Program Manager with an Air Force Deputy P.M. Assault Breaker was completed and available for transition to full scale development during this period. However the CSWS requirements, which were defined in a mission element needs statement and approved by DoD in April 1981, could not be fully achieved with the current architecture of the Assault Breaker program. Several concepts to meet the CSWS and JTACMs requirements were two stage missile systems drawing on modifications to fielded systems in the Army. The previously described T-16 and T-22 were modifications of Patriot and Lance. Other concepts were based upon modifying the Pershing booster and the Nike Ajax booster, or a cruise missile concept put forward by the Boeing Corporation that had experience with several other cruise missile efforts that were in design or production.²² The marriage of these programs and the question of the transition to full scale engineering development of an "Assault Breaker" type system complicated each service's attempt to continue their separate development of munitions to meet their stated requirements for interdiction (Air Force) and the emerging "Deep Battle". The Air Force itself had diverse requirements brought forward by the Tactical Air Command (TAC) and the Strategic Air Command (SAC). The Strategic side of the house had similar targets and requirements to those that led the Army to the CSWS efforts. However, the Tactical Air Command needed to kill or suppress enemy air defenses (SEAD) at typically shorter ranges than those envisioned by the Strategic Air Command or the Army. Beyond the range and threat requirements were form and fit constraints. The targets of interest in general were similar but the emphasis that each service put on the targets and the underlying need to engage these targets was still quite different. The Army put a priority on Command, Control, and Communications/Intelligence (C3I) with air defense assets following closely and then maneuver forces. The Air Force primarily was interested in SEAD targets, with anti-armor a distant second and C3I after the other two.²³ On the strategic side, a common rotary launcher was being designed and the larger 22 inch diameter of the T-22 would lead to both a redesign effort and to a reduced number of rounds carried. Similar concerns for the 16 inch T-16 missile were based upon the missile length and the ability of that diameter missile to carry sufficient cargo or warhead.²⁴ The Air Force requirements and interests, including the necessary air launch, resulted in length and weight requirements that are different from Army size and weight concerns for a surface launched weapon of this type. With the many successes of the Assault Breaker demonstrations there was an interest in both Congress and the DOD for the missile selected to utilize either the T-16 or the T-22. This "suggestion" was even included by the House-Senate conferees, of the 1984 defense authorization bill, limiting the missile component to using the T-16 or the T-22 design. Congress hoped to push the services toward an early start for an

engineering development effort.²⁵ The Air Force resisted the ballistic missile solution and still favored a standoff weapon tightly coupled to an air launch.²⁶

Mixed Requirements and Direction

The JTACMS effort awarded three firm-fixed price contracts for pre-full-scale development to Vought Corporation, Boeing Aerospace, and Martin Marietta in the middle of 1983. The awards were funded by the Air Force and the Army equally. At about this time the Initial Operational Capability (IOC) of the Multiple Launch Rocket System (MLRS) and the M270 Launcher occurred during 1983. In late January 1984, the three competing contractors each finish the firm-fixed price review of the capabilities and requirements match of their proposed system and requirements for the JTACMS system. At about this same time, the Department of the Army adds to the requirements that this mission should be filled by an extended range MLRS. In a series of agreements during 1984 the Army and Air Force

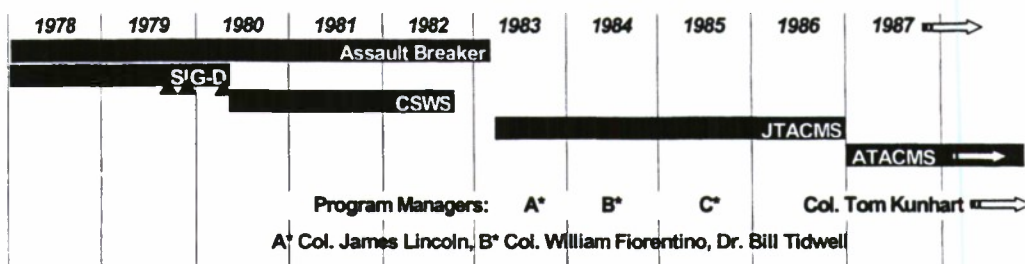


Figure 5 – An Overview of the Development Timeline

describe their future relationship and the method to achieve success using optimized technologies in the employment of AirLand battle concepts. Gen. Charles A. Gabriel, USAF Chief of Staff, and Gen. John A. Wickham Jr., U.S. Army Chief of Staff, signed a memo covering agreements on 31 separate points. This memo is later dubbed the "31 Initiatives" and covered many topics beyond JTACMS^{27 28}. The two services agreed to coordinate and be responsible for particular roles and missions. In this agreement the Air Force gained cognizance over the JTACMS efforts and would pursue a cruise missile. This development effort was then quickly classified. The classification led to speculation in the open literature that this may have been because the design hoped to make use of low observable technology or stealth technology. This speculation is later proved to be very astute. Also at this time, the Air Force had another classified project for an 'advanced cruise missile' under development by General Dynamics.²⁹ The development of highly classified technology in one service led to some of the chaos in developing a joint weapon to meet the needs of both services. In fact according to Dr. Billy Tidwell who was the deputy program manager during JTACMS and Acting Program Manager for a short period, the Army was "blindsided" by the Air Force. Apparently only a few people had detailed knowledge of the effort to include Gen. Shoffner at TRADOC.³⁰ This program and the heavily classified program's achievements help to bring about the split between the Army and the Air

Force in defining one system to achieve all of the objectives that each service desired. The residual JTACMS (Joint Tactical Cruise Missile System) development effort in the Air Force would emphasize a weapon with a range greater than 350 kilometers. With this range required, even a very high quality inertial sensor with a guidance update from a sensor element would have difficulty hitting reliably most targets without an onboard terminal seeker or other expensive update techniques. The cost of this approach eventually forced termination of this program and several others with the same focus during the next decade. By the end of August 1984 the Air Force officially ended its participation in the non-cruise missile portion of the JTACMS.³¹ Soon thereafter, DOD authorized a separate project to provide an interim cost effective capability to engage deep targets. One key constraint to the design choices reviewed and studied in planning this project was the burden in cost and manpower of fielding launch systems and ground support equipment to be used. In fact, Dr Tidwell recalls that the needed force structure requirements helped to eliminate many of the other system concepts. By choosing the Vought concept, the force structure used will be the MLRS launchers, soldiers and support. This project at first utilized the designation JTACMS-Army but was later modified to Army-TACMS. The path from the end of Assault Breaker to the agreements in 1984 and early 1985 were shaped by a number of factors and events both inside each service and in the world. One key element that fueled the requirements process was the results of studies that indicated that interdiction or "deep battle" would prolong the battle, and save manned aircraft in the process. Several studies have names such as "Battle King",³² however, many other studies explored different aspect of the approaches postulated and affected the decisions in the services and in OSD. This type of study result is critical to systems in this stage of development and helped to solidify the necessary support for JTACMS and then ATACMS. The Ft. Sill community and thus the "field Army" become an unwavering advocate for the system.

ATACMS – System Development

After the turbulent 1983 and 1984 period, with the requirements issues handled through agreements with other services and the needs expressed by DOD and Congress for a system which should utilize technology demonstrated in the Assault Breaker technology demonstration projects, ATACMS emerged and the Army quickly moved to begin a full scale development (FSD) effort. Following the November 1984 joint statement that reiterated the need for this type of weapon, the Army Materiel Command in January 1985, approved an essential document that describes the need and required functionality. This document is known as a ROC, short for Required Operational Capabilities. The Director of Combat Developments (DCD) at Ft. Sill, Oklahoma prepared the document. Ft. Sill is also the location of the Army's Field Artillery School and Center. Ft. Sill continued to be a strong advocate of the need for ATACMS.³³ Col. Thomas Kunhart took over the Program Manager duties from Dr. Tidwell who has served as acting Program Manager until Col. Kunhart could formally transition to this role. John Triac became the first ATACMS TRADOC System Manager (TSM). In this role, either

he or Col. Kunhart attended any meeting about ATACMS for the next five years.³⁴ The stability of having both a Program Manager and a TSM together for almost all of the EMD program and the good working relationship that developed is certainly one key feature in the development process of ATACMS. The Department of the Army also approved the ATACMS ROC in the middle of May, 1985.³⁵ The next month, June 1985, the Army issued a Request for Proposal (RFP) to develop a missile for second echelon attack. A key design element was the necessity of utilization of a modified MLRS launcher and the ability of the missile to be contained in the standard MLRS launch pod. This part of the acquisition was a limited competition for the firms that had participated in the Pre-FSD contracts. The second part of the acquisition is to be a sole source, non-competitive, award to the current manufacturer of the MLRS system, Vought / LTV. This route was justified by the fact that the manufacturer of the MLRS launcher would be the only company that could provide the necessary skill for integration of a new missile into the overall system.^{36 37} With the choice of LTV as the Prime contractor the government insured that the critical technologies were both important to the Prime contractor and that LTV had the needed experience and familiarity with critical technologies. This of course was brought about through the previously described efforts and the interactions with the lead government Science and Technology laboratory. (AML or Missile Research Development and Engineering Center) Groups that had a significant effect on the eventual system pushed several other requirements. The first was that the system should be self-contained and not rely on in flight updates from an airborne asset or the planned global positioning system (GPS). This requirement was made possible by the accuracy of the simplified inertial guidance technique and the use of the Ring Laser Gyro proved in Assault Breaker and SIG-D. Yet, this requirement moved the system one more leap forward away from the early overall Assault Breaker conception. Also, Gen. Thurman, the Vice Chief of Staff of the Army, required that there should be no visual distinction between which launchers had ATACMS and which launchers had the MLRS rockets loaded.³⁸ The concept behind this requirement is to make targeting of the higher value ATACMs more difficult for opposing forces because now ATACMS could be dispersed throughout the units that fire MLRS. Vought/LTV ended up teaming with Martin Marietta's Orlando division after Martin Marietta decided not to tender a bid. The Martin portion in this team would focus on the smart submunition warheads and parts of the guidance elements that they expected to become a major follow-on effort. Since smart submunition warheads were not part of the system fielded at the time of Desert Storm, they will not be covered in this case study. Boeing originally did not proceed with a bid. Later, Boeing decided to submit a bid and had to ask for relief from the original due date for the proposals.³⁹

In order to provide support and fully define the agreed-upon division of efforts, the Vice Chiefs of Staff of the Army and Air Force issued a joint memo, in July 1985, that describes support for a weapon to provide a near term capability for U.S. and European requirements. This memo also makes clear that the Army system will be fired from a modified MLRS launcher and that the Air Force will be the lead service on a joint tactical cruise missile.

Proposal receipt was closely followed by the decisions of the Army and Defense System Acquisition Review Councils decisions in December 1985 (ASARC) and February 1986 (DSARC). These decisions cleared the way for a system to move into full scale development. MICOM announced the award of two contracts to LTV Aerospace and Defense (LTV), for both the missile and launch pod container and the sole source award for integration and support equipment. The awards took place on the 26th and 27th of March 1986 respectively⁴⁰. The missile and launch pod contract was for 180.3 million dollars, and 83.0 million dollars was awarded for the required integration into the MLRS launch vehicle. This firm fixed price contract included an incentive of up to 6.5 million dollars if certain unit costs for production are maintained. The contract limited the production at price of each missile to \$250,000. This price did not include the APAM (anti-personnel, anti-materiel) warheads that were to be government furnished.^{41 42} In addition, the first 1000 production missiles negotiated for were to be produced for a fixed price. This type of fixed price effort shifts most of the risk to the contractor, who if they are to remain in business, must be able to meet this challenge without major setbacks in the development or with early production issues. LTV also must make the investment in the machinery and tooling required for production.

Key Technologies

This section will cover two key technologies that were successfully integrated during the ATACMS development. Each of these technologies will be explored along with the essential differences to current technologies and approaches used in other system that perform this same function.

Ring Laser Gyro

The Ring Laser Gyro (RLG) that found its way into ATACMS can be traced directly to the developments that were flown and tested in the SIG-D demonstration program. The RLG is an example of an optical type of gyroscope. Gyroscopes generally are used to provide information about the movement and orientation of an object. Utilizing various materials non-optical, wheeled designs use the measurement of forces relative to a spinning element to compute movement and rotation of a body. These designs typically involve a large number of mechanical components that must be designed, manufactured and maintained with great precision. Two advantages of RLG's are said to be:

1. "The device is much more tolerant of high vibration and g loads (up to 30 g's in boost phase) which lead to biases and inaccuracies drifts for conventional gyros"
2. "The RLG sensor has no problem in accommodating the high angular rates associated with strapdown units for small missiles"⁴³

The RLG was being used in laboratory environments and being explored for related systems when the system planning and pre-development work was started. However, by the time the system started FSD, the RLG technology had working

prototypes tested in a relevant environment. The FSD effort brought this technology to a flight qualified design which had been tested as part of a larger system.

Strapdown/Simplified Inertial Guidance

A "Strapdown" guidance unit eliminated several elements of previous guidance devices such as a stabilized inertial platform and the gimbals, and torquers that are required for the inertial platform. This setup allows for the accelerometers and needed gimbals to be strapped or mounted to the missile body. Therefore this type of device can handle the launch environment and will not suffer losses of precision that would be found in other devices used in this role.⁴⁴

This guidance architecture, while it makes use of the RLG covered in the previous sections, also covers the computers and the other system elements that use data from RLGs and other sensors. The inertial guidance system utilized is a Honeywell H700-A3 system. It was derived from similar designs in commercial aircraft but had several modifications for military use. The system uses a digital computer to analyze and process the data from the RLG. This computer is also used to perform the functions needed for navigation, guidance, and the missile autopilot. This architecture makes use of the transformation in digital devices that was surging in the commercial computer world at this very same time. The guidance system and the technologies used in the guidance architecture achieved similar maturity to that described for the RLG in the preceding section.

Testing Phases, DTI, DTII, & Initial Operational Test and Evaluation (IOTE)

The schedule for development test (DT) and initial operational testing can be seen in Figure 6. The test efforts were assisted with Hardware in the Loop (HWIL) efforts in parallel between the Missile Research Development and Engineering Center (MRDEC) and the contractor facility at Grand Prairie, Texas. Several challenges were handled during this phase of development. The testing began after the critical design review in the middle of 1987. The first DT test took place 24 months after program start. Several issues were explored during the next 27 (25 planned) test firings. This effort built upon successful developments during SIG-D and Assault Breaker. However, these are typical issues which this type of developmental testing is designed to find and engineer solutions before the final production design is achieved. The first of these is to show that the bomblets can achieve the appropriate shape in the target area. To achieve a useful dispense pattern for the bomblets, the missile must be spun at high speeds and the skin of the warhead section removed, which does not seem to be a difficult technology, however it offered some technical hurdles that had to be overcome. This area is an example of a seemingly simple technical integration task that can quickly grow into a much larger issue for a program in development if it is not handled well.

← JRCM APOMS →		1994		1995		1996		1997		1998		1999		2000		2001	
B Tides		QL TomKat FM														QL Mithras FM	
▲ (N4) JRCME ROC ▲ (Line) RFP Released		26Mr MLPA Aver(LTV 27Mr Integration Aver(LTV SiteSource		HayWMI MicroTests ▲ CIR		DIT 10Miles		▲ LRF1 65Miles ▽ DIT 15Miles		▲ LRF1 104Miles ▽ 100M 15Miles Deployment (RUG) Sud Asia 240PM6Fired Desert Storm		▲ RFP Mastrell DB Relay					
▲ ASRCI ▲ DSRCI																	
<div> <div>Mt Bollag in FM LTV</div> <div>Mt Bollag in VP, LTV & Bob Anderson FM</div> </div>																	

15

Subcontractor Problems

With the contractor phase of development testing nearing the conclusion of the original ten planned test shots, a major challenge and potential setback happened. The original subcontractor for the Control Actuation System (CAS) suffered from significant changes in financial position and also experienced a large turnover in management and technical staff. The subcontractor, Singer, went out of business. The loss of a primary subcontractor on this compressed schedule effort could have resulted in major schedule slips and significant cost impact. In this case, with a firm fixed price contract, and a 36 month warranty from the prime contractor, the government can designate the subcontractor loss to the program as "Low Risk". However, this issue is not as simple for LTV. They scrambled to review other suitable vendors and selected Simmonds Precision Motion Control, which is a division of Hercules. This issue was deemed so important to the contractor that the Program Manager for LTV, Mr. Bud Laughlin, moved physically, for the next six months, to the Simmonds plant in New Jersey to oversee the efforts and to help solve any issues as they develop. In fact, Mr. Laughlin believes this issue to be the major hurdle that was surmounted to deliver ATACMS on time and within budget. With a new subcontractor on board and with hands on management the new vendor ramped up and the test schedule was adjusted to phase in the new items. The new CAS design was cut in half way through the Developmental Test schedule. This tremendous effort by the Prime contractor exemplifies the type of management that LTV utilized with each and every one of the contractors on ATACMS.

Launcher Issues

The integration contract was being carried out in parallel with the missile system development efforts. A number of technical challenges had to be overcome to modify the existing MLRS capable launcher to be able to fire the ATACMS. One interesting area was an essential part of the fire control system that utilized "firmware". The use of software designed into the system on various chips necessitated work around software solutions in order to gain the needed functionality. Despite the software and other integration effort required, LTV rolled out the "Deep Attack" (ATACMS) launchers in July of 1989. According to Col. Dave Matthews, who took over from Col. Kunhart in April, 1990, the software challenges were critical to fielding a capable system. Assault Breaker testing again allowed for testing of items needed for a successful overall system. In order for the launch unit to properly initialize the missiles guidance section, the launcher must also have an Inertial Navigation System (INS) that is accurate enough to minimize error in targeting coordinates that will arrive from another reference point. Early prototypes were tested in Assault Breaker. The early Deep Fires launcher design would utilize a non-optical INS for this purpose. The technical issues, which LTV and the subcontractors hired for this integration effort had to address, involved modifying or working around decisions in both hardware and software that had been made to allow the launcher to fire rockets to a much shorter distance (MLRS). The difficult issue of important software elements design/test/deployment and the

integration of the missile system with the launcher were somewhat underestimated by both the Prime contractor and the ATACMS project office.

Lethality Issues

During IOTE (Live Fire) and at a critical time in system development, before the full rate production decision reviews, a major issue arose for Col. Matthews and the ATACM team. Fourteen days before the final milestone decision and Defense Acquisition Board (DAB) review, a prominent figure in the Pentagon review cycle brought up a "bombshell" that to some appeared to be an ambush. The Director of the Live Fire Test Office raised concerns from his analysts at the Institute for Defense Analysis (IDA) concerning the lethality of the systems main payload of M74 bomblets. These bomblets had evolved from BLU-63 and other bomblets from the Vietnam era and had been loaded into conventionally armed LANCE missiles. The question hinged around the exact effects of the tungsten fragments created by the exploding bomblets against the primary targets of the ATACMS system. One of the primary targets that the system was to be designed and tested to defeat was the SA-12, Surface to Air missile system. The analysts believed that the small tungsten fragments would vaporize and fail to hurt critical electronic parts inside of the system. The Live Fire official pushed for empirical data to demonstrate the effectiveness of the systems. Since the DAB review was scheduled within the next few weeks there was not time to provide a set of tests that would lead to "empirical" data without months of delay. This delay might have been palatable in most systems, however, because of a contract option negotiated at program award more than four years earlier, delay beyond the 1st of November, 1990 would allow LTV to renegotiate the price of the first production missiles. A review of the facts around the bomblets' abilities found that minimal analysis had been done and was cursory at best. However, without money budgeted for this effort and the time constraints involved the program faced a significant challenge.^{48 49}

A decision was made to pull together a quick demonstration test of the effectiveness of the system's bomblets to successfully damage surrogate parts after passing through panels of material set up to approximate the skin of the threat vehicles. Col. Matthews had to cajole (LTV) to purchase many of the materials for this test because the process that was available in the Army at the time would not have met the deadline. The Army Materiel Systems Analysis Agency (AMSAA), the primary operations research organization in the Army, verified the layout of the panels and components against the descriptions available of the threat vehicle. The only place in the country that had a method to spin the bomblets to the required rotation rate for the arming process to happen was at the Milan Ammunition plant. In order to lessen the chances of failing to obtain the needed data, a parallel test event was planned for the White Sands Missile Range (WSMR), however, without the machine for spinning the bomblets a less acceptable method of initiating the bomblets had to be used. This method, using a detonator instead of the fuze inside the spheres, could be viewed as a modification that could effect the data gathered.

Both sets of tests were accomplished and pictures and other documentation was collected to attempt to demonstrate the ability to defeat the required targets.^{57 58}

Col. Matthews also succeeded in having his boss, the Program Executive Officer for Tactical Missiles, convince senior management in LTV to extend for five days the pre-negotiated option in order to accommodate the review that ended up on the schedule for November 2, 1990. This review was set one day after the contract option was originally set to expire. After reviewing the pictorial results from the test events hastily planned and executed, the Live Fire group's objections were withdrawn as long as a commitment was made to fully characterize the effects in a follow on effort. This challenge to the program culminated in a successful review by the DAB on November, 2 and award of a full-rate production (FRP) contract on November 5, 1990. This contract was for 318 missiles at a price of 126.3 million dollars.^{57 58 50}

War imminent

Just prior to the events leading up to the DAB process described in the preceding section, Kuwait on the 2nd of August 1990 was invaded by their neighbor to the north, Iraq. The United States responded with operation Desert Shield as it built a coalition of forces to throw Iraq out of Kuwait. A decision was made to field ATACMS early by utilizing the IOTE unit, the 6/27th Field Artillery Battalion in August of 1990. One complete battery moved to Altus Air Force base and was airlifted by C-5's to the Gulf. The soldiers went over on other aircraft and the equipment was shipped over on naval vessels. The Battalion was originally put under the XVII Airborne, with Battery A later being moved under the control of the VII Corps. At this time, only 20 ATACMS had been delivered to the Army.⁵¹ Of the three batteries that were deployed only two could fire ATACMS and had Version 6 of the fire control software. In September the LRIP contract that was then underway, was accelerated to provide for more missiles to be available for use should they be required in the developing situation. The following January the contract was altered again to push the delivery of more missiles to the Gulf. This accelerated schedule forced the prime contractor to use a production process that "inspected in quality" during manufacturing to ensure that the missile produced were reliable missiles.

Gulf War success

First Firing

Shortly after Hellfire missiles fired by Apache helicopters changed "Desert Shield" into "Desert Storm", the ATACMS capable MLRS fire units were moving across the desert on the first night of the Air war. The first target, previously unknown, was detected by unspecified means and identified as an SA-2 surface to air missile site. Since the international air tasking order system had proved cumbersome, ATACMS was tasked with removing this threat. Because the units were on the move and had not fully integrated into the VII corps, the battalion commander and the soldiers on the fire unit ended up exchanging "the names of the

commanders' kids" before all parties were confident that this was a real tasking order. This was the first of several early difficulties in responding to the tasking. Every ten kilometers or so the position and azimuth determining system (PADS) had to be rezero'd to insure quality reference for the fire control software. The next difficulty was, "How to clear airspace?" Since the system could achieve up to about 132 kilometers and would be fired to about 100,000 feet to reach that range, a considerable amount of airspace could be reached. Apparently, the mechanisms to do this had not been established in the rush to bring this asset into operational use. The unit moved more than three times before launching a missile at the intended target. The software and the airspace clearance problems forced the system to go through a scenario that had not been encountered or planned for in training and the IOTE shots. The software problem kept this fire unit from putting a second missile on this target. In order to be sure that the SA-2 site was fully destroyed a second launcher ran the same mission in parallel. This launcher put an additional two missiles on the target and completed the first use of ATACMS in combat on January 18th 1991⁵². Col. Matthews indicated that it is unlikely that the system at the time of fielding would have been as successful if it had gone to a new group of soldiers who had little familiarity with the system. However, because of the experience gained by this group during the IOT& E phase and the real life experience of launching during Desert Storm, the software difficulties were handled and the missiles were launched at several types of targets during the rest of the conflict. Several SAM sites were targeted and destroyed. Other targets successfully engaged included, logistical sites, artillery and rocket battery positions and tactical bridges. The requirement to notify the U.S. Air Force before firing reportedly added two to three hours to the typical one hour time that was generally required to engage a target.⁵³

Spectacular Success

In all 32 missiles were fired during the remaining period of "Desert Storm". Many sources indicate that there was a 100% reliability of the system in these thirty-two firings. This reliability was attributed to the 100% inspection of the first production missiles. Later as LTV focused on process improvements, quality was brought about through the entire manufacturing process and not inspected into it. The production success was also made possible because the system prime contractor made use of the supplier relationships gained and the production skill and knowledge gained on the MLRS program. However, it was later learned by a chance encounter between a person who had performed Explosive Ordnance Demolition (EOD) work and Col. Matthews, that one of the missiles that was successfully fired had in fact been found unexploded and was later rendered safe. Since, records were kept of the EOD work, this data was mailed to Col. Matthews and the missile was tracked to the production lot. Since two missiles were fired at most targets, the system still engaged all targets with 100 percent success. However, one missile of the thirty-two fired during this period experienced a motor burn through. This important data helped the program in tracking the potential causes for this type of failure mechanism.⁵⁴ Many people involved in the combat utilization expressed positive opinions of the system and according to LTG Thomas

J. Kelly, who served as Director of Operations for the Joint Chiefs of Staff(JCS), ATACMS, "was spectacularly successful".. and it really delivered"⁵⁵

Summary

This case study has looked at the emerging doctrine, early technology and system experiments, system requirements, novel and important technological advances, and wartime success of the Army Tactical Missile System (ATACMS). The system development process delivered a militarily useful product to the hands of the men and women of the United States Army. The delays and missteps along the way can mainly be attributed to divergent requirements and interests of other actors outside of the Army. This serpentine development route must be viewed in light of the changing world situation and the doctrinal changes that were taking place at the same time as the technologies and systems concepts were emerging. However, as the data from Desert Storm indicates, ATACMS delivered a reliable, effective, and evolutionary conventional semi-ballistic guided weapon to be used meeting the many challenges involved in fighting under the Airland battle doctrine. In doing this and doing this well, the ATACMS system was poised to fulfill the revolution in conventional attack that was envisioned at the beginning of the Assault Breaker efforts. However, there are still technical challenges ahead to meet the promise of an all-weather, countermeasure resistant, clutter resistant, deep armor killer.

Program Management

It is hard to tribute the success of any system to the technologies and the processes alone without regard to the people who manage, create, and innovate. This system had many fine people who contributed to the overall success. Dr. Bill Tidwell participated in the early concept trade studies and served as acting Program Manager as JTACMS transitioned into ATACMS. He also served as the Deputy Program manager early in the ATAMCS development. Many factors point to the team created by Col. Kunhart and the relationships that were put in place with the TRADOC System Manager, Mr. John Triac. The relationship of Col. Kunhart with Mr. Triac helped to ensure that the system would have both the support of the eventual users, but also demonstrated that the user's input was a valuable and essential element in this successful acquisition program. Also, their relationship to the contractor lead Mr. Laughlin created an atmosphere fundamental to the successful development of the ATACMS system. The project office and the prime contractor jointly worked to put the proper people together to solve problems. This type of teamwork and collaboration is the hallmark of successful integrated product teams (IPT's) Col. Kunhart indicated that the project office worked as a "large happy family" with many non-technical staff being encouraged to attend test firings at WSRM to help foster the team spirit. Success later in the project timeline was linked directly to the efforts in gaining the production decision and to the Desert Storm usage that occurred with Col. Matthews in a leadership role. Col. Matthews and the Deputy Program Manager at the time, Mr. Don Barker, helped maintain and move forward the ATACMS system development. The real success is most likely found in the many people in both the ATACMS project office and at the LTV who

came to work and did the best job they could on the challenge of the day. Good management can create an environment for success but the people working in that environment are critical to success.

Firm Fixed Price- DoD Enterprise concept

The utilization of a firm fixed price contract in the full scale development effort in many ways was probably more influential in overall program success than the efforts to streamline the system acquisition process with reforms such as the DOD Enterprise system. This is where the Assault Breaker and the SIG-D programs must be given due credit. Without these demonstration programs and the time gained while the joint requirements were being pursued, it is unlikely that a Prime contractor would have been willing to sign up to a firm fixed price development effort. This is true even though the ring laser gyro and the other technologies were very important and familiar to the Prime contractor. The early testing and simulation work was a critical factor in the eventual contract method. Both government Program Managers cited this contracting method as a primary source of overall system success. Col Kunhart notes that the DoD enterprise status of the ATACMS system allowed for the reduction of official OSD reviews. However, in order to skip several of these reviews an enormous amount of paperwork still had to be prepared to comply with the regulations. The Army had not, at the time, embraced the concepts that were enacted in the Enterprise program and therefore most Army mandated reviews were conducted. Mr. Laughlin indicated that the effects of the Enterprise program were much less evident on the contractor side. He believes strongly that the firm fixed price nature of the effort allowed Vought to manage the program for success. Any firm fixed agreement where the contractor brings in the system "on time and the contractor makes a profit" is a successful system.

Bridge to the Future – Evolutionary Acquisition of a System of Systems

This story is only the beginning in the attempt to create a revolution in military affairs by living out the doctrine in the AirLand battle and the concepts of FOFA. The story of the ATACMS system is not complete without a look at the pre-planned product improvements(P3I). The ATACMS designed, built, fielded, and battle proven in this case study was designed to allow upgrades to payload and guidance to fully live out the potential of the 'Deep Battle' concept. As this case is written, testing is ongoing on several new payloads and uses for the ATACMS family of munitions. The uses include precision guided submunitions of several types which will add to the targets that the system can successfully engage. Diverse launch platforms to include ships, submarines, and strategic bombers also add to the ability of the system to affect any future conflict. This case demonstrates that the acquisition process can lead to the development of mature technologies, and successfully integrate and deliver them into weapon systems able to change the way future commanders can achieve victory.

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C
FOG-M

Fiber Optic Guided Missile (FOG-M)

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Fiber Optic Guided Missile (FOG-M)¹

During the 1960's and 1970's the former Soviet Union amassed large numbers of military personnel and equipment in Eastern Europe. Central to the Soviet offensive military strategy was the use of the tank. By the 1970's they had fielded more than 50,000 main battle tanks. U.S. military planners hypothesized scenarios in which the enemy would attack in narrow fronts with significant depth and massed firepower. It was posited that Warsaw Pact forces might lead with as many as 600 tanks against a U.S. division followed by subsequent waves of armored units. During this timeframe the Soviets had significantly modernized the capability of their tanks. The T-64, T-70, and T-72 tanks were faster and had superior armor than their predecessors. In addition, during this period they expanded and modernized their arsenal of artillery, aircraft, and other conventional weapons. In particular, they had increased the production and fielding of Mi-8 and Mi-24 helicopter gunships to be used in direct support of ground forces.

The Need for Innovative Weapons and the Emergence of a Product Champion

It was within this context of a massive Soviet buildup that the need became preeminent for innovative weapons to combat the superior numbers of Soviet tanks and other conventional weapons. During the early 1970's a young physicist, William McCorkle, with the Army Missile Command's Research, Development and Engineering Center (RDEC) developed a radically innovative concept for a new anti-tank weapon. McCorkle, who was already an accomplished physicist, had been experimenting with new technologies associated with remotely piloted vehicles. These pilotless drone aircraft, which were equipped with miniature television cameras and transmitters, could be used for reconnaissance and other military applications. McCorkle believed that systems could be developed which were equipped with warheads that could be used as anti-tank weapons. He called his concept the Fiber Optic Guided Missile or FOG-M because of its utilization of emerging fiber optic technology for guidance and control.

William McCorkle seemed to possess all the traits characteristic of the classic product champion. He was technically brilliant, persistent, unafraid of setbacks or temporary failures, and exhibited a level of dedication and focus that is necessary for any radical innovation to succeed given the many obstacles that inevitably must be overcome. His initial work on this concept not only included creatively managing his time at work in the laboratory, but countless hours in his workshop at home. By the late 1970's he began his quest to obtain the necessary support from the Army and Congress for the development of this radical new weapon system.

A Weapon System with Unique Capabilities

The missile that William McCorkle envisioned would be designed to engage tanks, other armored vehicles, high value ground targets (such as command, control, and communication centers), and possibly helicopters beyond the line of sight of the operator. The range was unknown at the time of concept inception, but he hoped to achieve a range that would be between 10 and 20 kilometers. This range would be well beyond the maximum range of tank main guns or direct fire anti-tank missiles. The system would consist of a gunner's station with between 6 and 16 missiles mounted on a High Mobility Multipurpose Wheeled Vehicle (HMMWV). The missiles would be launched toward a

target area based on forward intelligence information. After missile launch, the operator would be able to intervene at any time to lock on and engage detected targets. The operator would view the flight path and the target via a small TV camera equipped with a zoom lens mounted in the nose of the missile. Data would be transmitted to the operator's console by fiber optic cable that would unspool from the missile itself. Simultaneously, guidance commands would be transmitted to the missile on the same optical fiber from the ground computer located in the gunner station. After being vertically launched, the missile would cruise at low altitude below cloud ceilings as shown in Figures 1 and 2.

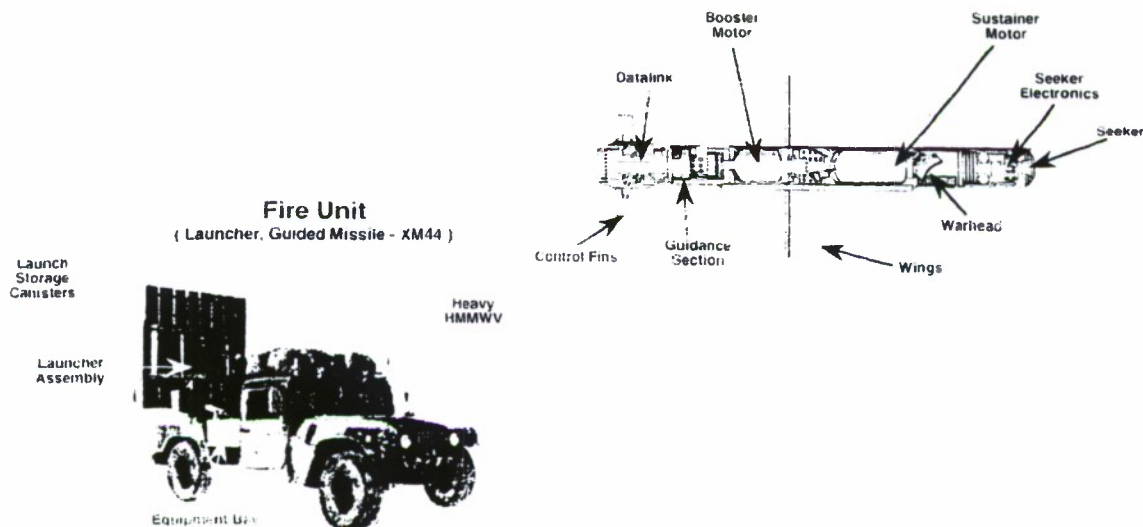


Figure 1 – FOG-M fire unit and missile

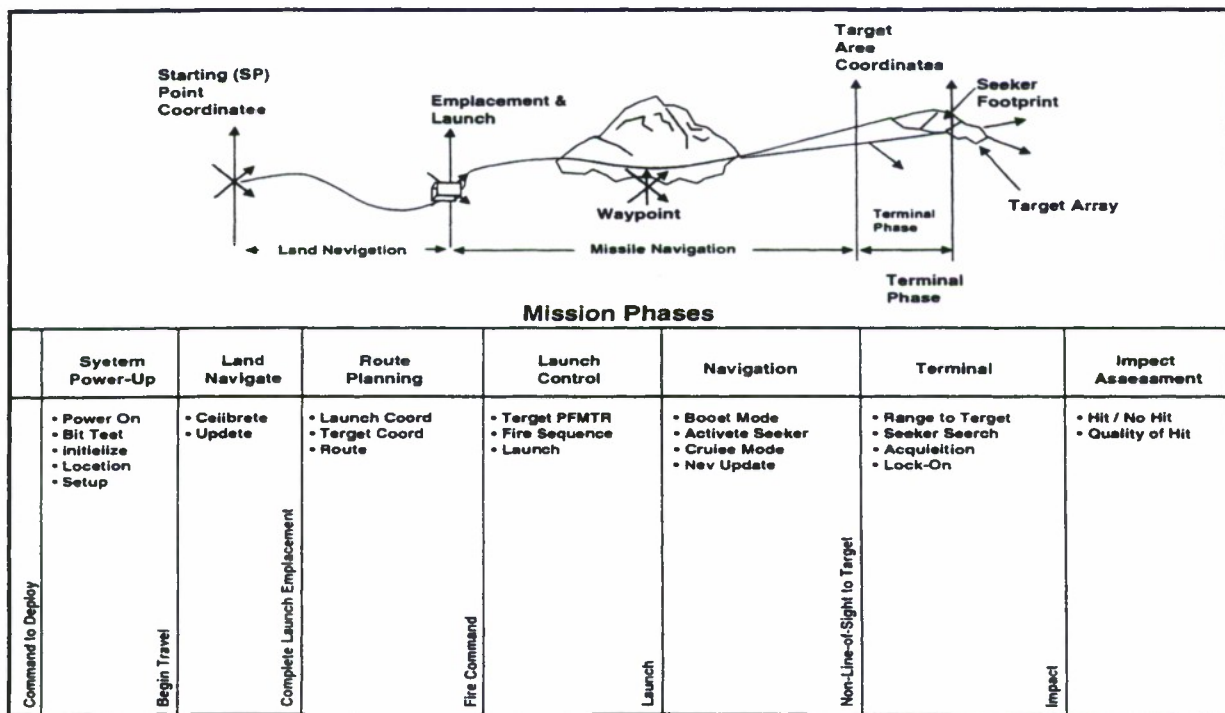


Figure 2 – FOG-M engagement concept

This missile had a number of potential advantages. By controlling the missile from the ground, most of the expensive hardware needed for guidance and image processing would be reused rather than destroyed with each missile. While original estimates for the cost of each missile (with daytime capability only) ran in the \$20,000 range, the missile actually had the potential to be quite cost effective. This is because the accuracy would allow for the use of fewer missiles to be used to destroy a target. Thus, the total number of missiles required would be less, resulting in overall reduced expenditures. FOG-M also operated from a concealed position. This would serve to protect the operators from direct fire. Because it had non-line of sight capability, the operators could locate and destroy targets behind hills and other barriers that other missiles or artillery could not detect and destroy. This was perhaps the most critical and unique capability of the system.

There were other potential advantages. Because the guidance data was transmitted through the fiber optic wire, enemy electronic countermeasures would be inoperative. Furthermore, the issue of available space on the radio frequency spectrum would never be problematic since the FOG-M had its own self-contained propagation medium. FOG-M's lethality was enhanced by the fact that it would not attack the frontal armor of a tank. Rather, it would be launched vertically, flatten out to a level flight path, and then dive at a steep angle toward the top of the tank. This, ostensibly, is where the armor is weak. In addition, because of FOG-M's ability to recognize targets, the probability of fratricide would be significantly reduced. Finally, this recognition ability also allowed for the simultaneous capability to perform reconnaissance.

The Product Champion Encounters Resistance

In his classic study of product champions, Donald Schon of MIT cites numerous examples of successful radical innovations where the product champion encounters continuous, and often relentless, resistance to his innovative concept. There are many reasons for resistance to radical new ideas and McCorkle found this to be true with FOG-M. In the late 1970's, in his first major attempt to obtain development funds, McCorkle briefed Army Deputy Chief of Staff for Research, Development and Acquisition, Lt. General Donald Keith on FOG-M. Keith was somewhat less than enthusiastic. He cited concerns such as range, whether the quality of the image would be sustained over the entire range, target acquisition, and the fact that the initial concept did not include night or adverse weather capabilities.

Dr. McCorkle was not discouraged by the lack of support from Lt. General Keith. His next strategy to obtain funding was to visit the various commanding generals at several Army centers in order to obtain their support. He first sought the support of the Armor center at Fort Knox. This seemed logical since FOG-M was an anti-tank weapon. However, he met with a general lack of support because the Armor Center was committed to combating the Soviet tank threat with the M1A1 tank with tougher armor and an improved cannon. He found that the Armor Center was committed to allocating research and development funds to acquiring a more lethal tank cannon, and any other efforts would be seen as diverting resources from that priority.

Next, McCorkle attempted to solicit the support of the Artillery Center at Fort Sill. The Artillery Center, however, saw FOG-M as a weapon that was somewhat foreign to traditional artillery. During this timeframe, they were committed to developing the

artillery shell known as the Copperhead that was essentially a laser guided anti-tank round. Thus, there was a lack of support from the Artillery Center as well. To make matters worse, the Artillery thought that FOG-M should be an anti-aircraft weapon. Furthermore, air defenders thought that it should be an anti-armor weapon, and the Infantry believed that FOG-M should belong in the Artillery. This was a weapon with tremendous tactical potential, but did not fit neatly into one of the Army branches. The result was that it was believed to have potential, but could not get the full support of any single Army branch.

In spite of this general lack of support, by 1979 FOG-M was receiving limited funding from the MICOM Research, Development and Engineering Center using what is known as 6.2 discretionary R&D funding. The FOG-M effort was structured to allow phase-in and testing of technology advances as they became available from other 6.2 funded efforts. In November 1980, Dr. McCorkle was named director of MICOM's Research, Development and Engineering Center. This was a positive development because it would allow him greater access to discretionary funds that could be used for FOG-M development. Nonetheless, these resources were comparatively meager given the level of funding which would be required to develop a major weapon system such as FOG-M.

The Product Champion Obtains Executive Sponsorship

In Schon's research on new product development, he found that invariably, in large scale product development efforts, if the product champion was not able to obtain a high level executive sponsorship, the product died. In 1982, FOG-M's fate was influenced in a very positive way. That year, Undersecretary of the Army, James Ambrose, became convinced that FOG-M had significant potential as an anti-tank weapon. In addition, that same year Anthony Battista, the top staff member on the House Armed Services Committee's research and development subcommittee, became convinced of the weapon's potential. This high level sponsorship was instrumental in securing the necessary funds to begin serious development in the RDEC laboratories.

Dr. Paul Jacobs of the Guidance and Control Directorate assumed the role of program manager and worked closely with McCorkle on the development effort. Jacobs created what can only be described as a classic skunkworks in the laboratory. He put together a team that consisted of individuals from all of the RDEC labs in order to develop a FOG-M prototype. With no prime contractor, but numerous contractors with limited tasks working side by side with RDEC engineers in the lab, and minimal administrative overhead and control, work progressed at an accelerated pace. In 1982 alone, the team completed the detailed investigations and systems analysis required to define the FOG-M concept that would be developed and tested in the following two years. Specific accomplishments included the design and fabrication of prototype folding wing systems for the vertically launched missile, the definition of the imaging seeker requirements through captive flight tests, target array/system performance analyses, and acquisition experiments, the completion of parallel designs for the motor and control system, and guidance schemes in preparation for hardware tests.

The Laboratory Achieves a Huge Success

With the increased funding support, by 1983 the FOG-M program achieved the status of a 6.3A Technology Demonstration Program. To make the skunkworks operate with maximum efficiency and flexibility in terms of personnel assignments, Paul Jacobs employed a matrix structure. Various individuals were assigned responsibility for specific components with flexible staffing arrangements whereby proportions of individuals' time were assigned from the various laboratory directorates. Jacobs bootlegged support from others such as administrative support personnel.

By the end of 1983, after six successful development tests, the launcher and test vehicle were certified for flight evaluation by AVRADCOM. By the end of 1984, the aimer had been designed, built, and tested. The aimer function was to aim the test rounds to aid in data reduction. The aimer was the first of its kind and allowed for external, automatic aiming by being attached to the missile. During 1984 a cost efficient control system for FOG-M was developed and demonstrated in hardware-in-the-loop simulations and four flight tests. This in-house laboratory development was the result of a well coordinated team effort among actuator hardware designers and control systems analysis and modeling engineers.

Because one of the major objections to FOG-M had been the issue of night and adverse weather operation, in 1984 seven fixed-price contracts were awarded to allow laboratory and field evaluation of industry infrared sensor concepts applicable to a low cost seeker for FOG-M. In addition to the hardware evaluation, each of the contractors performed a study to support their concept as a low cost solution for an infrared sensor.

The System Engineering and Production Directorate provided hardware fabrication and integration support. The Propulsion Directorate developed flight weight motors with a minimum signature solid propellant booster and a low rate composite solid sustainer. A liquid propellant sustainer was also designed, tested, and delivered for flight testing. Propulsion parametric analysis and design concepts were prepared for a 10 kilometer range system demonstration. Four man-in-the-loop flight test rounds successfully demonstrated the propulsion system by the end of 1984. During the flight tests two alternative launch concepts were demonstrated. These included a solid motor eject with wing deployment, and boost ignition in flight and boost from the launcher with predeployed wings. The protection of the optical fiber during missile launch from an enclosed launch pod was also demonstrated. Finally, by the end of 1984, the initial FOG-M rate stabilized vidicon seeker and the first three 10 kilometer fiber optic links were procured and tested for the first guided flight tests.

During 1985, the Structures Directorate continued its effort at minimizing the launcher packaging volume and weight. A new air transportable launcher containing 12 missiles was developed for the HMMWV. This system would be vertically erected on the bed of the HMMWV using onboard hydraulics. The vertical launching of missiles would enable greater packaging density on carrier vehicles and would permit gunners to operate from concealed positions, improving crew and launcher survivability.

During 1985, the Advanced Sensors Directorate continued its efforts toward the development of a low cost infrared seeker. This sensor would provide the full 24 hour and degraded environment operational capabilities. Based on the contractor findings initiated in 1984, the team investigated the infrared imaging concepts offering the greatest potential cost advantage. Work began on the design and fabrication of three

seekers that used a focal-plane array sensor. Another development included an expanded data link capability that eliminated much of the onboard control electronics.

During this same year, the Guidance and Control Directorate completed integration and testing of the multitarget handoff correlator for midcourse guidance. This device had important utility when multiple targets existed in a single geographic location. In this case, the references used to guide the first missile automatically guided subsequent missiles to the target area. Under these conditions several missiles guided from a single gunner's station could be in flight simultaneously. Consequently, the human operator could not manually perform multiple tasks. However, since the correlator could be shared between several missiles, the automatic mode could achieve this multiple missile scenario.

Concurrently, an automatic system for winding the optical fiber on a special spool was designed. The baseline system consisted of a mandrel on which the fiber was wound, a lead screw which would advance to the rotating mandrel, a control system for maintaining prescribed winding tension and a microprocessor system for controlling the total system's operation.

By mid 1985, multiple man-in-the-loop flight tests had been conducted. These tests demonstrated automatic fire control and launch, vertical launch from a canister, automatic cruise at low altitude, control by the operator to maneuver the missile trajectory manually during the cruise mode, operator detection of the target, lock-on and terminal engagement of a moving tank target, and the utility of the digital multimode target tracker. Then on June 1, 1985, the FOG-M prototype achieved its first successful hit on a moving target. In an incredibly brief two year period, the skunkworks operation of the MICOM RDEC labs had achieved a stunning success. At this point the history of FOG-M, under the leadership of William McCorkle and Paul Jacobs, read like a chapter out of Peters' and Waterman's best seller, *In Search of Excellence*.

The Non-Line of Sight Project Office is Created

An unexpected event occurred in 1985 that had important implications for FOG-M. Defense Secretary Casper Weinberger made the decision to cancel the Army Air Defense Center's DIVAD anti-helicopter gun that was also known as Sgt. York. The program had been over budget, behind schedule, and had experienced performance problems. This created an opportunity for FOG-M, not as an anti-tank weapon, but as an anti-helicopter weapon.

In November 1985, McCorkle conducted a test in which an Army corporal was given minimal training and then successfully hit a helicopter parked behind a hill ten kilometers away. In a second test, a helicopter moving at 100 kilometers per hour was destroyed. These tests captured the attention of Major General Don Infante of the Air Defense Center at Fort Bliss because nothing else in the inventory had the potential to hit a helicopter utilizing a "pop up" tactic behind a hill. This also caught the attention of a number of high level Pentagon officials, including Defense Secretary Weinberger. FOG-M was repositioned from being an anti-tank weapon to being an anti-helicopter weapon, and the decision was made to accelerate FOG-M development and to conduct the Initial Operational Evaluation.

In December 1986, the Under Secretary of the Army for Acquisition designated FOG-M as the Non-Line of Sight (NLOS) system for the Forward Area Air Defense System. In July 1987, COL Oleh Koropty was named Project Manager of the NLOS

Project Office, and George Williams was named Deputy Project Manager. George Williams was replaced by Jerry Dooley in late 1988 when Williams was named Fire Support Deputy PEO. The NLOS Required Operational Capabilities (ROC) document was approved in October 1987.

The full scale development request for proposals (RFP) was released in November 1987 and amended in February 1988. Two teams of defense contractors bid on the project, Martin Marietta and Raytheon, and Boeing and Hughes. The full scale development contract was awarded to Boeing and Hughes in December 1988. On paper, Boeing and Hughes were to split the work equally. Boeing was responsible for the ground equipment and Hughes was responsible for the missile. The Boeing Hughes bid was \$131 million and this low cost bid resulted in the contract award. However, a project office cost and operational effectiveness analysis (COEA) conducted that same year estimated over double the cost for the full scale development phase. This would represent the seeds of trouble to come.

In 1988 NLOS had been budgeted at a level of \$63 million. By 1989 budgetary resources allocated to the program totaled \$144.2 million. By the end of 1989 the total staffing of the NLOS Project Office was up to 72 civilian and two military personnel. The NLOS Project Office worked with RDEC in the technology transfer of FOG-M engineering data to the Boeing Hughes team. The Technology Transfer Steering Committee consisted of the Project Manager, PEO, test, prime contractor and user representatives. The project manager at Hughes was George Haynes and the project manager at Boeing was Alex Henshaw.

Simultaneously, the NLOS Project Office supported the RDEC Technical Risk Reduction (TRR) program. TRR was mandated by Congress and was designed to demonstrate complementary designs and hardware, incorporating knowledge from the lab R&D into the full scale development phase design in an effort to reduce technical, cost, and schedule risk. The TRR program was designed to provide assistance in the highest risk areas where RDEC expertise was available. Contributions made in the components area were on imaging infrared seekers, variable speed low signature propulsion, high payout speed fiber optic data link, more accurate midcourse navigation, alternate warhead designs, and automatic target cuing tracking. In the system area, contributions were made on aerodynamic design, wind tunnel evaluations, software development, system integration, and flight testing.

In the effort to coordinate the TRR activity, Korohey and Dooley initiated the Cost Reduction Working Group in April 1989. While Hughes made more effective use of the RDEC data, Boeing preferred to take an approach whereby they would, in the estimation of Dooley and McCorkle, invent their own version of FOG-M with the consequent patent advantages. Hughes' engineers were noticeably upset with Boeing's approach. Paul Jacobs hypothesized that this was not only motivated by patent advantages, but was also a case of the NIH, or "not invented here" syndrome. Boeing's view of the situation, however, was different. Robert Foss, Boeing Marketing Manager for Tactical Missiles, observed that the Boeing team felt they were taking an appropriate approach and that Hughes was being uncooperative by attempting to position themselves advantageously for the forthcoming production contract. Jim Daniel, Boeing FOG-M chief engineer, maintained that the military specifications imposed by the NLOS project office were excessive and required the significant design changes. In any case, the failure

to take full advantage of the development accomplished by engineers in the RDEC labs was also a seed of serious trouble soon to come.

Just as full scale development was beginning to progress, an ominous setback occurred. This was the Presidential Budget Directive #104 in December 1988 that deleted approximately \$77 million from the NLOS procurement funding for FY 90/91. This event would have a serious impact on the program schedule. To make matters worse, by the end of 1989, Boeing's progress on the ground equipment was beginning to slip seriously behind schedule. Jerry Dooley believed this was due, in part, to the fact that Boeing had assigned a team to FOG-M that had just completed work on the large Air Force B2 Bomber contract. The team was accustomed to working on much larger Air Force projects, and this contributed to a disproportionately large allocation of time during the first year to activities other than design and testing. In the late 1980's, Boeing had not yet developed a strong base of expertise in smaller missile systems. This would develop to a greater extent in the 1990's. Tom Jarrell, Boeing Deputy Project Manager for FOG-M, and Bob Foss agreed that insufficient familiarity with several of the emerging technologies involved in the system proved to be problematic. For example, Jarrell observed that problems like the stability of the fiber optic bobbin device in storage through temperature and humidity cycles proved to be significant technical challenges. Jim Daniel, Boeing FOG-M chief engineer, also observed difficulty with the stability on the infrared seeker. Problems such as this contributed to the slow pace of progress. In addition, as previously noted, Jim Daniel believed that the military specifications articulated by the NLOS project office were excessive. Numerous specifications, such as survivability in an environment of nuclear exchange, added development cost and schedule time.

By September 1989, the Initial Operational Evaluation had been completed. This involved captive flight, missile firings, and Force Development Test and Experimentation phases. The follow on Extended User Employment test began in June 1989 with a series of single and dual missile firings at White Sands Missile Range and concluded in June 1990. In spite of this progress, in December 1989, all NLOS procurement funding was deleted from the President's budget submission. Procurement funding was then restored via the Program Objective Memorandum building process. At this point funding stability was becoming increasingly problematic.

In 1990 the full scale development contract experienced significant cost overruns. These overruns were attributed largely to Boeing and Hughes unrealistically low bid for the full scale development contract. At this point, cost containment measures were formulated by the NLOS project office in conjunction with the contractors. The initial cost containment efforts were consolidated and incorporated into an engineering change proposal document designed to baseline the contract into a more realistic target cost and insure that future overruns would be reduced. Cost containment measures included the decision to produce only the NLOS light fire unit mounted on a HMMWV chassis, which would be delivered to both heavy and light divisions. At this point, the project office planned to follow the full scale development contract with a maturation modification contract. This contractual instrument would be designed to accommodate required system testing not provided for in the initial full scale development contract. It also provided for contractual coverage for FY93-94 necessitated by the production funding delay.

Thus, by September 1990, the In-Process Review approved the restructured \$630.8 million baseline for the NLOS program. In addition, by the end of 1990 the Initial Operational Evaluation and the Extended User Evaluation testing programs produced a 58% success rate with the IOE type missiles. In the operational testing military personnel engaged moving and hovering helicopters, and moving and stationary tanks that were out of the line of sight of the firing unit. These tests extended to distances of 10 kilometers. By the end of that same year, critical design reviews had been conducted for 69% of the system principal components.

The Boeing Hughes Contract is Cancelled

Despite the IOE success and the significant progress that had been made, by late 1990 the cost overrun issue was receiving high level Pentagon attention. Then a decision that was disastrous for the program occurred at the time of the Gulf War in January 1991. Army Acquisition Executive Stephen Conver made the decision to terminate the Boeing Hughes contract. During this time period the Department of Defense had been under increasing pressure from Congress and the public to reduce cost overruns in weapons procurement. Mike Kelly, a former Hughes engineering manager, hypothesized that Conver wanted to make an example. The perspective of the NLOS project office was similar. Jerry Dooley observed, "It turned out that FOG-M was sitting in the wrong place at the wrong time, because he was looking for an example, and there we were, with our estimates showing us way over [budget]". Conver explicitly stated that the reason for the cancellation was excessive cost growth. However, Dooley, McCorkle, and Jacobs posited that this was actually a secondary reason. The primary reason may have been the prioritization of other systems over FOG-M based on the assumption that multiple threat scenarios could be countered with an alternative deployment of systems, or possibly the acquisition of another missile system developed by the Israelis that Conver favored. In any case, whether or not this decision was optimal has been the subject of some controversy.

Lesson 1: A Flaw in the Acquisition Strategy can have Serious Consequences

The acquisition strategy of the NLOS project office was very similar to that of many other systems in development during the late 1980's. The full scale development effort was a cost plus incentive fee contract awarded to the Boeing Hughes team. The contract was to extend for 43 months. The design to unit cost provisions carried an award fee based on an evaluation that was to be conducted after limited production buy 1 (LP1). This would be followed later by a second evaluation of LP2 and LP3. The limited production buys would be sole source contracts to the full scale development team. Both of the contractor team members would be required to produce the system under a firm fixed price follow on limited production contract. Furthermore, both team members would be required to be qualified for full scale production prior to any FSP award. Following the completion of full scale development, the two team members (Boeing and Hughes) would then compete for the full scale production contract. This contract was to be a firm fixed price contract. Figure 3 presents a summarization of the planned milestones based on this acquisition strategy at the time of the start of full scale development.

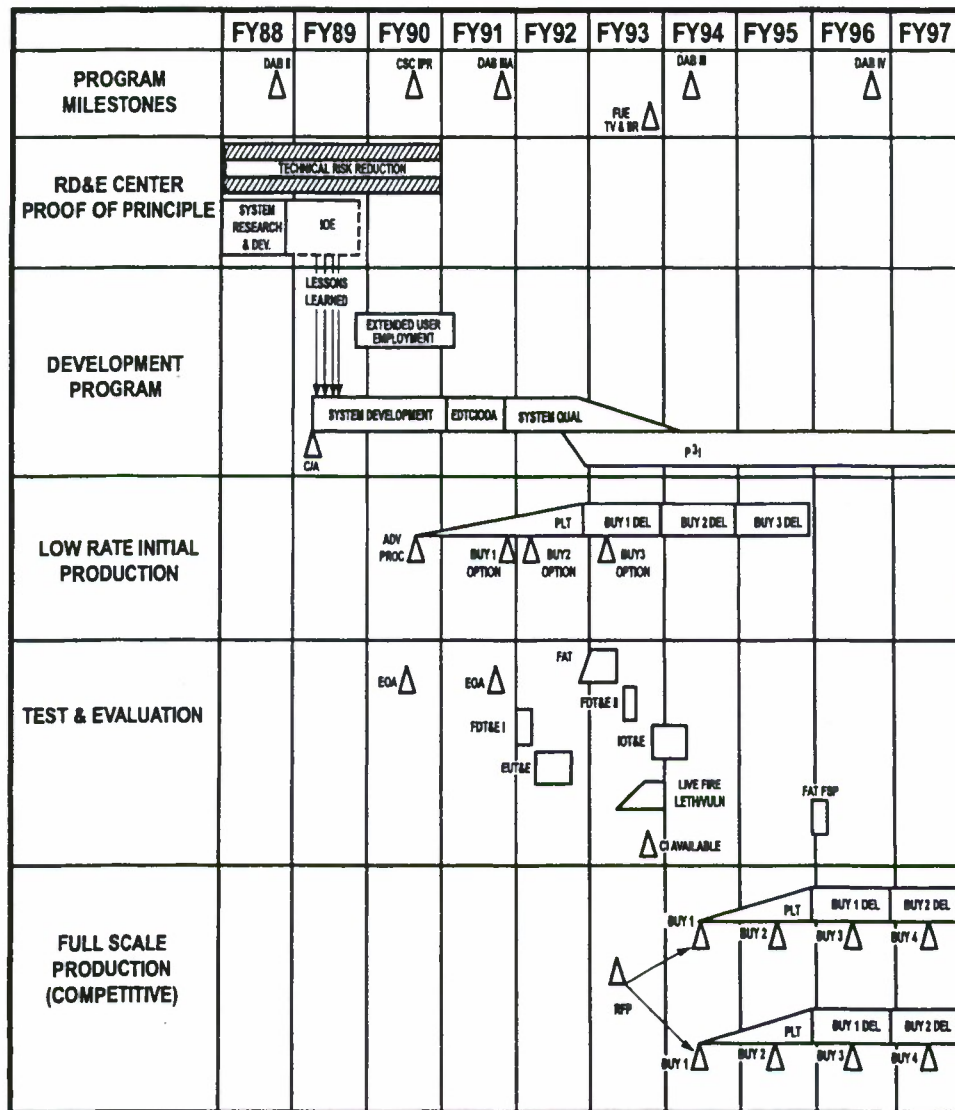


Figure 3 – NLOS acquisition strategy

A cost plus incentive fee contract can work well in a number of contexts. For example, when Boeing was competing against Vought for the large Multiple Launch Rocket System (MLRS) production contract, Boeing's behavior was radically different. This was because the production contract was so large (significantly larger than FOG-M), and Boeing and Vought were competing during full scale development on the basis of technical performance and cost effectiveness. In the case of FOG-M, the incentives were different. First, the incentive in the contract was not significant compared to the income that could be generated by escalating costs. Paul Jacobs observed that the main reason Boeing was not making full use of the engineering development that had been completed in the lab was because the incentives were inadvertently structured to generate more cost in order to maximize income. There was simply insufficient incentive to fully utilize the technology developed by RDEC engineers. The financial incentives favored maximizing hours of engineering design work, and in essence, reinventing FOG-M. Furthermore, cost overruns had become common in many large defense contracts in the late 1980's, and

Boeing management simply did not believe the government would ever cancel the contract.

One approach to counter this problem would have been to create a series of critical milestones with evaluative testing. Such testing would include component level testing, and other design evaluations, in addition to actual flight testing later in the schedule. Failure to meet schedule, cost, and technical performance objectives at each critical milestone would then result in significant financial penalties and/or withholding of significant incentives. At each critical point a go/no go decision, or the option to cancel would be available. One can only speculate, but instituting such controls in the areas of schedule, cost, and technical performance may have been beneficial.

Another fundamental error occurred during the Boeing Hughes selection process. The Boeing Hughes team bid \$131 million for the full scale development contract. Their strategy was, ostensibly, to come in low with the full understanding that cost overruns would be inevitable later. The NLOS project office had conducted its own cost estimates including detailed risk analyses. Their own estimates were well over double the Boeing Hughes bid, in the range of \$343 million. What appeared to be the rational decision at the time was made. The contract was awarded to the low cost bidder. Unfortunately, this decision had serious implications later. By signing the contract at \$131 million, cost overruns were inevitable. In a high visibility program like NLOS, the magnitude of the overruns which began to materialize two years into the full scale development program were simply too large to avoid the scrutiny of Congress, GAO, and high level Pentagon officials. The resulting cancellation was a devastating setback to the program.

Paul Jacobs observed that another potential issue with the acquisition strategy was the fact that Boeing and Hughes were teamed for the full scale engineering development phase. However, at the conclusion of this phase they were to compete for the production contract. This arrangement would not create conditions conducive to full cooperation and collaborative sharing of technical knowledge. Rather, there would be a significant incentive to be cautious regarding the sharing of any unessential information in order to create an advantage for the forthcoming production competition. From Jacobs' vantage point, the level of cooperation between Boeing and Hughes was weak during the full scale development. Both Ken Matkovich from Hughes, and Bob Foss from Boeing agreed that cooperation was less than ideal.

A final issue with the acquisition is associated with the selection process. Hughes had an excellent base of experience and expertise relevant to the technologies involved in FOG-M. Boeing, as noted earlier, in the timeframe of the late 1980's had yet to develop a high level of internal expertise with some of the technologies associated with small missiles. According to Jacobs, they lacked a high level of expertise in a number of the key areas. Jim Daniel noted that Boeing had moved a number of people from Seattle who were accustomed to working with other technologies on large aircraft. As a consequence, the learning curve was greater. Therefore, while the technology readiness level may have been relatively high based on the RDEC development work, the actual readiness level was not as high at Boeing. Based on these observations, one might conclude that the proposed staffing for the effort may not have been sufficiently scrutinized in the selection decision process. This also may have contributed to the schedule slippage during the first year of full scale development.

Lesson 2: Integration and Control Could Have Been Improved through Modes of Organizational Design

It has been established that the integration of the engineering development completed in the RDEC labs and the work of the contractors was less than optimal. As noted previously, the contract itself did not facilitate integration between the contractors and the lab. The effort on the part of the NLOS project office to initiate the Technology Risk Reduction program and the creation of the Technology Transfer Steering Committee were very useful devices. However, even though they were necessary, they were not sufficient to achieve the required level of integration, or technology transfer from the lab to the contractors. A more profound organizational design solution was needed.

In the research literature on organizational design, this type of problem is commonly addressed with the creation of cross organizational teams. These teams exist under many different labels such as design-build teams, platform teams, integrated product development teams, etc. In the case of FOG-M, the full scale development contract itself would have needed to specify in detail the structure of these teams which would consist of contractor engineers, RDEC laboratory engineers who participated in the early development, and project office personnel. RDEC laboratory personnel would not perform management functions, but would either be collocated with contractor personnel to perform the actual technical work or be allocated specific tasks. Detailed specification of how funding would be allocated among the various participants would be a necessary part of the contract. This approach has worked effectively in other programs such as the joint effort between Vought, the MLRS project office, and the RDEC labs in developing a guided version MLRS. What cannot be overemphasized, however, is that the financial model articulated in the contract must promote collaboration rather than create a profit incentive to not collaborate.

The concept of integrated product development teams emerged in the 1990's. Jim Daniel, Boeing chief engineer on FOG-M, believed that in the 1988-90 timeframe the coordination between Boeing and the government could have benefited significantly from such teams. In the subsequent work on EFOG-M, between 1994 and 1999, with Raytheon as the prime contractor, integrated product development teams were utilized. This was actually one of the first major Army contracts in which integrated product development teams were employed. In this application, teams were created that consisted of both government and contractor personnel. For the fire unit-platoon leader's vehicle, there were teams for the equipment bay, the vehicle mod/launcher, the cab equipment, and the system software. For the missile, there were teams for the seeker section, propulsion, the warhead section, the missile airframe and canister, the aft section, and the data link. For system engineering, integration and test, there were teams for system design, system simulation, system integration/test, and command, control, and communications. Had such a concept been implemented during the Boeing Hughes contract, technology transfer between the lab and the contractors would have been facilitated. However, it is important to note, as Jim Daniel observed, that the performance of such teams is always a function of the quality of the participants in terms of their technical skills and their willingness to cooperate. Hence, the optimal form of organizational design is only a necessary, but not a sufficient condition for high levels of cross organizational integration.

Lesson 3: The Central Problem in FOG-M Development was Unsustained User Support Due to Suboptimization Resulting in Funding Difficulties

From the very beginning FOG-M encountered problems with user support. This was a problem for William McCorkle, the project managers, and the deputy project managers, both government and contractor. This was a weapon that by all indications could have effectively served the Infantry, the Artillery, or Air Defense. This was because the weapon had an uncommon degree of versatility in potential military applications. However, the Infantry had a very traditional viewpoint, thinking in terms of direct contact with the enemy within a range of roughly four kilometers. FOG-M was to be deployed at greater distances and destroy enemy targets remotely. Thus, while the system could have been potentially very useful to the Infantry, their culture was characterized by traditional (as opposed to futuristic) thinking. This may be why the Infantry viewed FOG-M as something foreign to their mission.

In a similar way, the Artillery viewed FOG-M as a weapon that would be deployed in ways that did not fit with their traditional mission. Furthermore, they had prioritized other weapons and were committed to those development and production programs. Consequently, the Artillery viewed FOG-M as a weapon that belonged in Air Defense. In the late 1980's, following the cancellation of the DIVAD program, Air Defense did give a high level of support to the FOG-M program. However, this support was limited to a period of time in the late 1980's and early 1990's. With the cancellation of the full scale development contract with Boeing and Hughes, a multiyear window of opportunity was lost.

One reason FOG-M had difficulty attracting support from one of the Army branches is that it was not a basic upgrade or replacement for an existing system that was becoming obsolete. Therefore, it had no established constituency. One might conclude that a major contributing factor to the support problem was that the Army suffers from an organizational structure deficiency sometimes referred to as "stovepipes". Here the stovepipes are the Infantry, Armor, Air Defense, Field Artillery, etc. FOG-M was a radical new innovation that simply did not fit "neatly" into one of those stovepipes. However, this weapon had such potential lethality and versatility that in the wider sphere of battle planning it could have tremendous utility. Thus, it appears that this is a case of the problem that the management literature refers to as suboptimization. Each branch is individually maximizing based on their decision criteria, but the combined outcome is suboptimal.

One way the problem of support might have been approached is through what the management literature on overcoming resistance to innovative change labels "joint diagnosis". This concept has its basis in the social psychological literature on persuasion and attitude change. The basic concept is to refrain from proposing a technological solution and then attempting to sell that solution to a potential customer. Rather, one engages the customer in a process of joint diagnosis (of needs or requirements) and then jointly works toward the development of a weapon concept to address the threat. Through an iterative process that would involve projected cost comparisons with other weapons, a joint solution might emerge. In this way the customer sees the solution as, at least in part, his solution, resulting in a greater level of "buy in" or commitment. Since the mid 1990's, RDEC has instituted annual meetings with TRADOC representatives for discussions that

could facilitate such a process. Unfortunately, this was not in place during the 1980's and early 1990's when it might have benefited FOG-M.

Since FOG-M was competing against other systems for resources, it may have been beneficial earlier in the program to utilize cost effectiveness data more extensively to make the case for FOG-M development funding. Such analyses would be subject to greater error at early stages because the data would be incomplete. However, while the cost per missile was expensive, the accuracy in testing was so high that the number of missiles utilized in combat, when compared to other weapons, would be predictably low. Thus, overall cost effectiveness was a major potential benefit of FOG-M. The absence of data, however, made it more difficult to convince decision makers of the merits of this system based on cost and operational effectiveness criteria.

During the 1990's, several U.S. allies developed and fielded systems based on the FOG-M concept. These included Japan, Israel, Sweden, and a combined French, German, and Italian program. This, in and of itself, is evidence of the viability of the system. This development suggested another avenue by which FOG-M may have acquired resource and political support during the 1980's and early 1990's. A joint venture or strategic partnership with one or more of our allies would have increased the potential base of financial resources and also increased the political support for the system. An example of where this strategy worked very well was the development of MLRS during the early 1980's with the U.K., West Germany, and France. Given the ostensible international interest in a missile system with FOG-M's capabilities, a well timed strategic partnership may have succeeded in providing the necessary resources to accelerate development.

A final issue regarding adequacy of funding support is fundamental to large scale engineering projects in general. The annual budgeting cycle works well for almost all federal agencies. In the case of large scale engineering projects in the Department of Defense, this budgeting system does not work well. This is because the very nature of large scale multiyear engineering projects requires sound project planning and rational financial planning over the multiyear schedule of the project. In industry, while annual budgeting is the norm, long term financial planning is instituted without the continuous threat of funding perturbations based on politicized decision making processes. Under the existing governmental system, annual funding threats and perturbations are endemic. From the perspective of sound engineering project management, the current system of funding large scale defense projects is in need of reform.

Lesson 4: Changing Requirements has Adverse Consequences for the Development Schedule and Costs

By the mid 1980's, the work in the RDEC labs had been so successful that FOG-M was well on its way toward the completion of engineering development. However, a combination of factors in the years following, with the creation of the NLOS project office, the cancellation of the contract, and the subsequent restart of the program, resulted in escalating costs and schedule delays. Decisions were implemented to give the system both TV and imaging infrared seekers, changing the propulsion system from a solid propellant rocket to a variable speed mini-turbine engine, increasing the range requirements to 20 kilometers, increasing the weight of the warhead which changed the specifications for the missile, developing two versions (light and heavy) for the HMMWV and the M993 tracked vehicle, developing the capability of guiding two

missiles simultaneously, and approving the later combined arms version that would be capable of destroying both tanks and rotary wing aircraft. The combined effects of these and other requirements changes had very real consequences for costs and schedule. When the RDEC lab prototype was completed, the technology readiness level was comparatively high on most components. However, with the increased requirements specified in the NLOS Required Operational Capabilities document of October 1987, the technology readiness level was reduced.

Paul Jacobs attributed the problem of "requirements creep" to the shifting of support bases over time and the short position tenures of high level military decision makers. According to Jacobs, the proclivity of military decision makers to institute requirements changes is always based on good intentions. But the net effects on schedule and cost are often underestimated. According to Jacobs, the problem is compounded by the fact that proposed requirements changes are often accompanied by funding uncertainties. A failure to accept the proposed requirement change may result in loss of funding. This continuous threat to funding influences technical decision making in a way that increases technological risk.

Clearly, what was needed was an Operational Requirements Document that specified requirements at a high level of technology readiness and saved upgraded capabilities that involved less mature technologies for future preplanned product improvements. This is of course what the NLOS project office sought. However, the need to secure funding served as an impetus to increase technological risk. This resulted in prolonged development and escalated costs.

Epilogue: The Enhanced Fiber Optic Guided Missile (EFOG-M)

Following the cancellation of the Boeing Hughes contract, during the period of the Gulf War, an NLOS Task Force was commissioned to review the Army's requirements for a non-line of sight capability. In March 1991, the NLOS Task Force, TRADOC representatives, and the AAE agreed on a basic set of NLOS capabilities. These included both an anti-tank (Infantry) and anti-helicopter (Air Defense) requirement. In July 1991, an ASARC meeting resulted in the approval of the NLOS Combined Arms (NLOS-CA) program. At this time, Colonel Louis Kronenberger was chosen to assume the position of project manager to transition the program from the terminated full scale development program into a pre-demonstration/validation program. The reports of the U.S. Senate Armed Services Committee and the U.S. Senate Appropriations Committee directed the use of \$25 million from FY 91 rescission funding in FY 92 to reinitiate the program. While this level of funding was austere, the R&D activity could continue in the RDEC labs. During the remainder of 1991 through 1994, work continued on TV seeker modifications, warhead testing, design of the electronic safe and arm device, the fiber optic dispenser, the gunner station, autopilot software, simulation development, the EM actuator, and wind tunnel, variable temperature, shock, and vibration testing.

Although funded through 1994, in September 1993 the Army cancelled funding for the NLOS-CA in the FY 95-99 budget estimate submission. This, however, was only a short setback to the program. The Office of the Secretary for Defense continued working on a program review proposal to develop fiber optic guided missile technology. Budgetary resources were identified for FY 95 and outyear funding for a longer range

Enhanced Fiber Optic Guided Missile (EFOG-M). The EFOG-M program was designated by the Office of the Secretary of Defense as an element of the Rapid Force Projection Initiative (RFPI) Advanced Concept and Technology Development (ACTD) program.

The EFOG-M demonstration program request for proposals was released in March 1994 and amended in May and June 1994. Concentrated efforts were made by Louis Kronenberger and Jerry Dooley to incorporate innovative acquisition concepts such as government/contractor teaming in the form of Integrated Product and Process Development Teams, data items reduction, and minimized military specifications and standards. The contract was an incentive fee contract. Following the RFP, proposals were received from four contractors. The Source Selection Evaluation Board awarded the contract to Raytheon in October 1994. However, because of protests from the three unsuccessful offerors, a review by GAO delayed the official awarding of the contract to Raytheon until May 1995. The result was approximately eight months of lost time in EFOG-M development. However, as J.P. Ballenger of Raytheon observed, the major milestones of the program were tied to the Rapid Force Projection Initiative (RFPI). Therefore, the EFOG-M program schedule was compressed from the beginning in May 1995. The end point in the program schedule did not change because of RFPI's schedule. Adding personnel to mitigate the compression would have greatly increased program costs, so Raytheon performed admirably under difficult schedule and cost constraints.

In May 1995, Colonel Roy Millar was named Louis Kronenberger's replacement as project manager. During this period the total staffing of the project office ranged from 18 to 21. This was approximately one third of the staffing level during the Boeing Hughes FOG-M contract. The budget in 1994 was \$35 million and \$30 million in 1995. This level of funding was quite limited and influenced the rate at which development could progress.

The first phase of the contract was a simulation phase that lasted approximately 12 months. Phase I included the completion of two stationary simulators, one fire unit mobile simulator, one fire unit load of missile simulator, and one missile surrogate. Phase I also included the preliminary design work on the EFOG-M hardware and software to support the design review at the end of Phase I. This review also included a virtual prototype experiment. During this period, an Early Soldier Evaluation program was conducted with the Infantry at Fort Benning. This program followed the trend in industrial new product development by giving the user the opportunity to provide early feedback to the EFOG-M design team. As a result of this user testing, the gunner console and Battle Command Computer were relocated, the reload process was altered, the equipment bay hardware was enclosed, and the gunner console joystick design was modified. Following Phase I, Phase II was the demonstration phase that began in late 1995 and was scheduled to be 42 months in duration.

Deputy project manager, Jerry Dooley observed that the relationship between the project office and the contractor was dramatically different when contrasting Raytheon in the 1995-98 EFOG-M program with Boeing in the 1989-91 FOG-M program. An effective level of cooperation and completely open communication regarding cost and technical issues was characteristic of the relationship between Raytheon and the project office. Dooley noted that coordination between Raytheon, the project office, and the RDEC labs was extraordinary in terms of timely response to technical challenges. In

addition, there was a concerted effort at cost control, and requirements changes were controlled as well during the EFOG-M program.

The EFOG-M program remained essentially on schedule, and all of the major technological challenges had been resolved by 1998. The enhanced system had day/night capability with the infrared seeker. It was also capable of hot launch (as opposed to the use of an erection device for launch), and it had extended range. The engineering development was completed, and all that remained was the final stage of man-rating safety testing before production could begin. Then everything began to unravel. From the very beginning support from the Infantry had not been exceptionally strong. They had prioritized other systems like Javelin, TOW, and LOSAT above EFOG-M. There were substantive tradeoffs. If the Infantry was to procure quantities of EFOG-M missiles, reductions would occur in the acquisition of other weapons. The cost per missile was relatively high, but this had to be considered in light of the small production numbers. Raytheon argued that the cost would decline with increases in production over time, as was often the case with other systems. Nonetheless, the Army Chief of Staff and the Assistant Secretary of the Army for R&D made the decision that the Infantry would have to choose between EFOG-M and LOSAT. The rationale was that the acquisition of both systems would be too costly in light of overall budgetary constraints. The Infantry chose LOSAT. In 1998, the EFOG-M program was cancelled by Congress.

Conclusion

The 1998 cancellation of the production program appeared, at least on the surface, to be the end of EFOG-M. However, this may not be the end at all for one important reason. No other system in the Army's inventory has the unique capabilities of EFOG-M. Nothing else has the combination of non-line of sight capability, large bandwidths so that exceptionally detailed images are transmitted, the freedom from electronic countermeasures, high velocity reconnaissance capability, the ability to destroy both tanks and helicopters, and a 20 kilometer or greater range with extraordinary accuracy. This unique combination of capabilities suggests that it may be only a matter of time before the Enhanced Fiber Optic Guided Missile reemerges.

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Endnote

¹ This case utilized interviews from some of the same respondents as the Rosenau references. It also overlaps through January 1988 with the Rosenau case and epilogue. However, the issues examined in the case study, in terms of lessons learned, vary significantly from the references noted above so as to warrant a separate case study.

**D
GUARDRAIL
COMMON SENSOR**

Guardrail Common Sensor

Guardrail Development Prior to Common Sensor

The history of the U.S. Army operation of Special Electronic Mission Aircraft (SEMA) began during the Vietnam War. The need for signal intelligence (SIGINT) was significant during the Vietnam conflict, and as a consequence, improving the capability of these systems became an important Army priority.

During the late 1960s, the critical Army program that was to be the next generation SEMA was the CEFLY Lancer. However, the CEFLY Lancer program had been burdened with problems. There had been large cost overruns, major schedule delays, equipment weight problems, system integration deficiencies, and other management problems.

During this same timeframe, ESL of Palo Alto, California had been developing ground based COMINT systems that solved an important tactical problem. In Vietnam operators that were utilizing the ground based receivers were continuously being overrun by the North Vietnamese. As a consequence, many operators were being killed, and equipment and classified information was lost. ESL developed a system where sensors were placed on top of hills at strategic locations. The operators would then be located at a safe distance in a non-combat area. The sensors would collect the information. This information would be transmitted back to the operators at the remote location. Analysis and reporting back to the commanders would occur from the remote location.

Based on the successful development of ground based systems in Vietnam, in 1970 the National Security Agency (NSA) under the guidance of its director, Admiral Gayler, initiated the development of an airborne COMINT system with more advanced capabilities. It was believed that an airborne system using a remote ground station had a number of advantages. In addition to the superior COMINT capability for intercepting HF, VHF, and UHF communications, the fact that the plane would only carry two pilots meant reduced loss of life in the event that the plane was destroyed. Furthermore, by having analysts located at the ground station rather than on the plane itself, a much larger number of analysts could be instantaneously utilized. In late 1970 contract proposals were submitted by ESL and E-Systems. In February 1971 the contract was awarded to ESL for the development of what would be known as Guardrail I.

In Guardrail I the sensors on the aircraft would allow for an expanded view of the battlefield. The system included three RU-21G aircraft. The 18 operators would be located on the ground in three 40 foot trailers. The collection operators tuned in signals, monitored their tactical content, and gisted or tape recorded the intercepted signals. The analysts would enter important data into tactical reports that would be transmitted directly to the commanders in the field. The initial testing demonstrated that the ESL digital receiver designs used in Vietnam in conjunction with the Explorer COMINT remote transmitting system would operate effectively on an airborne platform, even in a dense signal environment.

Guardrail I was completed on an extraordinary schedule for just \$6 million. The system was delivered to Germany in August 1971 just in time for the Reforger exercises.

Guardrail performed remarkably well in this operational test. An operational need that Guardrail I did not provide was the capability to locate the position of enemy communications. During Guardrail I development engineers at ESL began developing an electronic direction finding system. This system would calculate the vector for the emanating source. Then with multiple platforms (aircraft) one could triangulate to calculate the approximate location of the communication source. This direction finding capability was then authorized as a product improvement program in April 1972. This system would be called Guardrail II.

Integration of the direction finding capability required an inertial navigation system. As a consequence, NSA obtained six residual RU21-E model aircraft that already had integrated the ASN-86 inertial navigation system. The aircraft were also modified to include the necessary antennae. The original Guardrail I microwave link required upgrading to support the direction finding link requirements. Further, the air-to-air relays were upgraded from VHF to UHF to reduce interference. Software was developed to support direction finding calculations and reporting. The output provided overlay of lines of bearing on map coordinates. This work was completed in approximately six months and the Guardrail II system was fielded in late 1972.

By late 1972, the US Army had an airborne COMINT system in Europe that had demonstrated the force multiplying factor that was to become central to the US/NATO defense strategy. Guardrail II had the capability of providing daily data on military buildups and the identification of emerging threats. Following the completion and fielding of Guardrail II, preplanned product improvements were completed that included minor enhancements, the production of spare parts, and further logistic support. Upon completion, this system was deployed in Europe in late 1973 and was called Guardrail IIA.

Following the completion of Guardrail IIA, in 1973 NSA initiated a twelve month program to produce another Guardrail system for the Pacific region. This system would be called Guardrail IV. It included an improved version of the UHF communications datalinks and a new generation of broader coverage VHF receivers. The basic system capabilities were essentially the same as the GR-II, but it also included an improved set of auxiliary ground equipment (AGE). The GR-IV system included six modified RU-21E aircraft. The GR-IV system was designed, built, and tested on schedule and within budget. The Army Security Agency (ASA) assumed responsibility for supporting the fielded system and maintained a small group of contractor field service representatives. The system was fielded in South Korea in 1974.

Guardrail I-IV achieved their operational requirements and were each produced on schedule and within budget. These early systems were procured by NSA as Quick Reaction Capability (QRC) programs. They were designed as theatre level assets which led to a long term requirement for Guardrail as an Army Corps level asset.

In early 1976, the Guardrail V program was conceived and ESL continued the program as prime contractor. The GR-V program was planned as a cost effective, second generation technology insertion program.

In 1977, as a result of the Intelligence Organization and Stationing Study, responsibility for the Guardrail program was transferred from NSA to the Department of the Army, Electronics Command (ECOM). Thereafter, with the creation of the Communications and Electronics Command (CECOM) and the Electronics Research and

Development Command (ERADCOM), Guardrail was assigned to ERADCOM. (In 1985, the Guardrail program was reassigned to the Intelligence and Electronic Warfare Program Executive Office at Ft. Monmouth with CECOM. At this time ERADCOM was renamed Army Research Laboratories). With the ostensible success of the Guardrail program, and the long history of cost overruns, schedule delays, and technical performance and integration problems, the Army's CEFLY Lancer program was cancelled. Guardrail became the Army's SEMA system.

Unlike the contracts for GR I-IV, the GR-V program had formal data requirements that included logistics, a qualification test program, a formal integrated system test program, a spare parts program, a quality assurance program, and formal software documentation. However, GR-V was still classified as a limited production urgent system. In this sense, while GR-V lost some of the skunkworks-like characteristics of GR I-IV, it still retained the authorization to proceed as an urgent QRC program with significantly reduced oversight requirements.

The original plan was to produce four Guardrail V systems. Each would have six aircraft. Beech continued as the aircraft modification subcontractor. The aircraft were derived from the various versions of the existing RU21 aircraft, including the RU21-E, A, D, and G aircraft. Each of these aircraft were modified to the GR-V specific RU21-H configuration. These aircraft were outfitted with wing tip pods that replaced many of the individual antennae that the GR I-IV aircraft carried. The aircraft also had provisions for radar warning equipment; they had low reflective paint, and were equipped with chaff and flare dispensers. GR-V included lighter, smaller direction finding equipment that created more space for the heavy UHF link and radio frequency antenna multiplexing equipment that was needed to connect multiple communications transceivers and on-board radios to the same antenna.

GR-V included a new computer system with increased memory and processing capability. Software improvements included computer assisted diagnostics and link frequency algorithms. In addition, improved direction finding calibration and automated direction finding accuracy test software were added.

The first GR-V system was completed in 28 months, on schedule. Following operational testing, this system was fielded in Gruenstadt, West Germany in 1978, replacing the GR IIA system. Two additional GR-V systems were delivered to Korea and the continental US in one year intervals (1979 and 1980). These systems replaced the aging GR-II and GR-IV systems. The original plan called for a fourth GR-V system to be produced. With the initiation of the contract for the Improved Guardrail V program, the fourth GR-V system was diverted to support the Improved Guardrail V program.

ESL was awarded the contract for the Improved Guardrail V (IGR-V) in late 1981. Beech would again assume responsibility for the aircraft subcontract. The IGR-V aircraft would be the first to be pressurized to allow for higher altitude missions. The aircraft would be the RC12-D. One of the major weaknesses in the preceding Guardrail systems was the inertial navigational system reliability. Navigation was critical to the direction finding capability and it was also essential to insure that the aircraft would not drift across the border into enemy territory during peace time missions.

Another requirement for the IGR-V was the integration of the Interoperable Data Link (IDL) for interoperability with the Air Force and the Navy. The IDL originated as a

wide band microwave link designed by Sperry Univac (Unisys) for the Air Force. Guardrail improvements to the link in establishing interoperability included dual Ku/X band tracker operation, error encoding, bulk encryption, a wider band uplink, and enhanced link diagnostics. The IDL vastly increased Guardrail's link capacity and also added anti-jamming features.

One of the major challenges for the Guardrail program was operating in a high density airborne signal environment. For IGR-V the pre-planned product improvements included the addition of the Fast DF (direction finder) that had been developed by ESL under an Air Force contract. In addition, ESL had developed a Signal Classification and Recognition System (SCARS) in its laboratories. The addition of Fast DF and SCARS to IGR-V allowed for auto search, auto DF, area of interest screening, and vastly increased direction finding throughput volume with greater emitter location accuracy.

The direction finding and signal processing improvements incorporated in IGR-V made it significantly more powerful than its predecessor, GRV. The first IGR-V system was completed in 1984, and operational testing with the 5th Corps in Wiesbaden, West Germany occurred in October, 1984. The second IGR-V system was completed and delivered to the 7th Corps in Stuttgart, West Germany in the spring of 1985. Both systems met their production schedules and budgets. In addition, both systems successfully met their technical performance objectives during operational testing.

The Guardrail Common Sensor Program is Launched

While the Improved Guardrail V systems were being completed, in 1982 a concept began to emerge for an advanced system that integrated other communications intelligence (COMINT) and electronics intelligence (ELINT) systems with Guardrail. This would be known as the Guardrail Common Sensor. It would combine the Advanced Quicklook (AQL) and the Communications High Accuracy Airborne Location System (CHAALS) with Guardrail to form a corps level signal intelligence system with an integrated platform and a single ground processing facility.

One of the primary advantages of the Guardrail Common Sensor (GR/CS) over its predecessors was its capability to simultaneously collect both communications intelligence and electronic intelligence. The ability to intercept non-communications emitters, such as radar, allowed the Army to retire its aging fleet of Grumman RV-1D Mohawks. These planes carried the Quicklook II Elint system that had become the Army's airborne electronics intelligence system.

Development of the Quicklook Elint system had begun in the early 1970s. With GR/CS a new generation of Quicklook would be developed that employed the technology known as Time Difference of Arrival (TDOA). This technology utilized triangulation from multiple aircraft to obtain location coordinates. The TDOA capabilities of GR/CS would give the United States a technology advantage over any other country. However, in order to achieve the integration for the GR/CS system, the AQL would require miniaturization due to weight and space limitations. The contractors for the Advanced Quicklook were UTL in Dallas (for development) and Emerson Electronics and Space Division (ESCO) in St. Louis (for production).

The second system that was integrated into GR/CS was the CHAALS precision COMINT location system. This geolocation system for communications emitters utilized both the TDOA technology and Differential Doppler technology. The CHAALS

development program began in 1972 as a joint Army/Air Force initiative. IBM developed the coherent processing and emitter location capability. The initial program in the 1970s was the Emitter Location System (ELS). This evolved to the 1980 Coherent Emitter Location Test (CELT). CHAALS evolved from these programs, and IBM continued as the contractor.

In order to achieve the high accuracy required for artillery targeting, both AQL and CHAALS (and other GR/CS systems) required the integration of the Navstar global positioning system (GPS). The airborne GPS receivers provided the required aircraft precision location and precision timing. With these developments the GR/CS location finding accuracy for both COMINT and ELINT improved from a radius of approximately one mile with IGRV COMINT to a precise location accuracy to support targeting requirements.

Work on GR/CS began in early 1985 and ESL continued as the prime contractor. The government program office that managed the project was moved from ERADCOM (this later became Army Research Laboratories) to Ft. Monmouth with the Communications and Electronics Command (CECOM), and the support of the Electronic Warfare Reconnaissance, Surveillance, and Target Acquisition Directorate (EW/RSTA). The program reported to the Intelligence and Electronic Warfare (IEW) Program Executive Office. Major Robert Dull was named product manager for GR/CS.

The basic operational concept behind GR/CS was to authorize one GR/CS system per aerial exploitation battalion in the military intelligence (MI) brigade of each corps. A standard system would consist of 12 aircraft that would fly operational missions in sets of two or three. The ground processing for GR/CS would be conducted in the integrated processing facility (IPF). The IPF would be the control, data processing and message center for the overall system. It consisted of four 40 foot trailers with 28 operator stations. Interoperable data links would provide microwave connectivity between each aircraft and the IPF. Reporting would then be transmitted to the Commanders Tactical Terminals (CTT). The CTT's would be located at up to 32 designated intelligence centers and tactical operations centers. The automated addressing to CTT field terminals would provide automated message distribution to tactical commanders in near real time. The CTTs were complete with anti-jam capabilities. The system later added a satellite remote relay system (RRS). With this system, intercepted SIGINT data could be transmitted to any location in the world. In addition, the system included maintenance facilities, storage vans, a power distribution system, and auxiliary ground equipment. The auxiliary ground equipment would include the automated test equipment used in preflight checks and maintenance. The SEMA aircraft for GR/CS would be derivations from the RC12 Beech military utility aircraft.

Software for GR/CS would include approximately 500,000 lines of code. Four mainframe computers were required to support each system. Communications frequency coverage was extended with low band and microwave intercept. More automated signal search, acquisition and recognition features provided significant flexibility and operator efficiency to the signal collection process. The system would also provide near first syllable detection via the priority audio monitor and priority audio recording. GR/CS would be designed to address the evolving threat that included the use of high density and heavily encrypted communications, wider frequency ranges, and low probability of

intercept techniques. A diagram summarizing the GR/CS operational concept is presented in Figure 1.

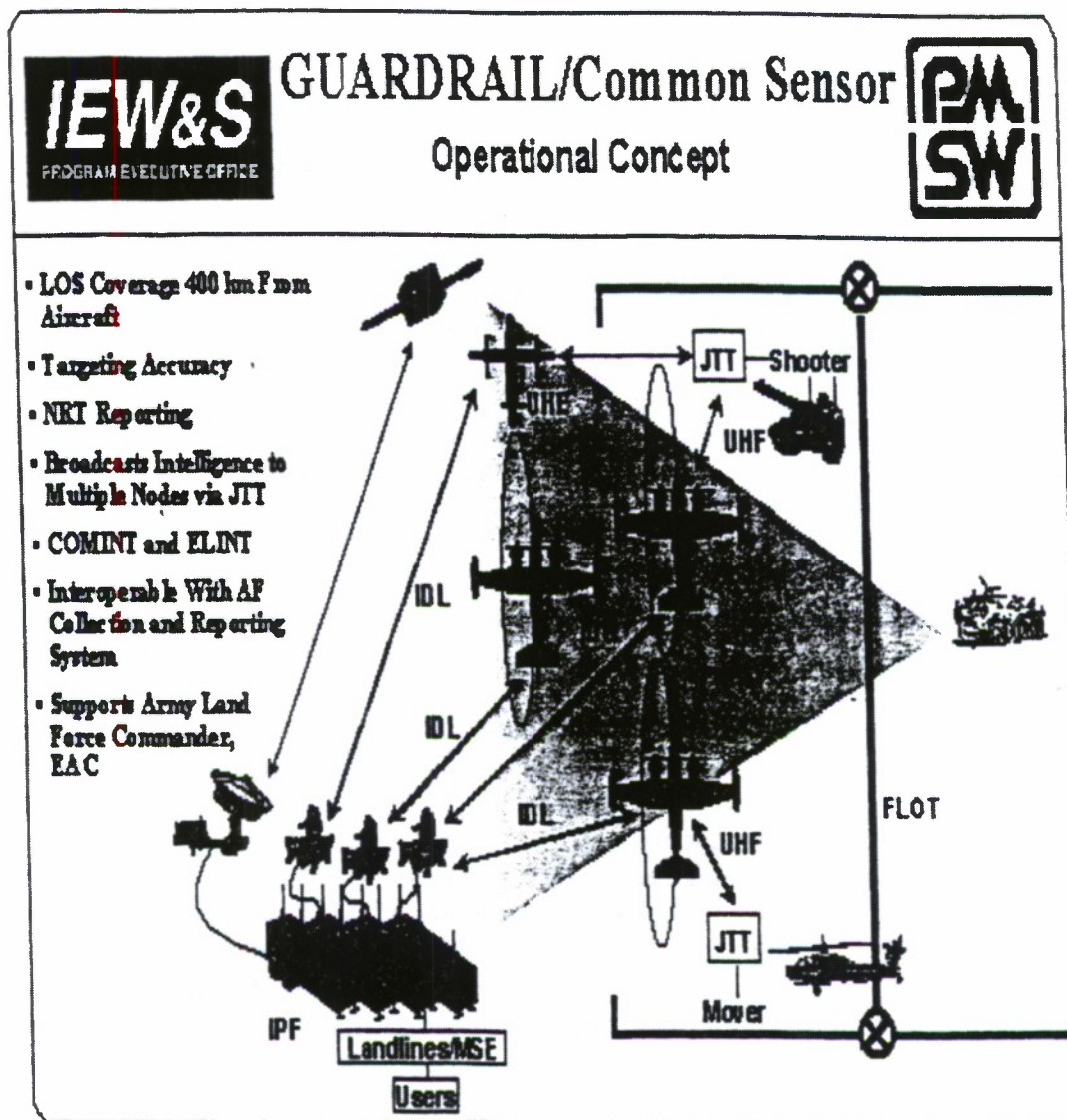


Figure 1 – Guardrail common sensor operational concept

Guardrail Common Sensor System 3

The original program plan for the Improved Guardrail V had been to build four systems, one for each Army corps. However, the plan was modified as the GR/CS concept emerged in 1982 and then actually went into development in early 1985. The remaining two IGR Vs that had been authorized would not be built. Rather, these would become Guardrail Common Sensors, Systems 3 and 4. Following their completion and fielding, two more GR/CSs would be produced and these would be named System 1 and System 2 to complete four GR/CSs with one deployed in each Corps. The program plan

also included an ambitious technology insertion or program of pre-planned product improvements with each successive GR/CS system. Hence, the sequence of order would be System 3, System 4, System 1, and System 2.

As work progressed on GR/CS System 3, by the end of 1985 ESL had integrated and successfully completed testing on the engineering development models of AQL that had been developed by UTL and produced by ESCO. Through 1986 progress continued on approximately 35 procurement work directives that encompassed the scope of the pre-planned product improvements to be integrated into the GR/CS System 3.

By the end of 1986, the air worthiness tests had been completed for the Beech RC-12H aircraft that would serve as the aircraft for the GR/CS system. Due to schedule considerations, six RC12-D aircraft were modified to the RC12-H configuration for GR/CS System 3. System 3 was to replace the aging GR-V system in Korea which was in need of replacement because the aging fleet of RU21-Hs used for GR-V. Because of the mission workload in Korea, the replacement was an important priority, and this became a schedule constraint for the System 3 program.

The testing for the RC12-H aircraft included an important oversight, however, and this would be the basis for a serious problem that would soon emerge. This problem would mark the most serious schedule setback since the Guardrail program had been initiated. When operational testing began in early 1988 at Moffett Field outside of San Francisco, it became apparent that the RC-12H aircraft would not be able to handle the added weight of the new GR/CS system. In project planning, it had been assumed that the RC-12H would be adequate, but the planning assumptions were ostensibly incorrect. The RC-12H had an increased maximum takeoff weight of 15,000 pounds. This was an improvement over the RC-12D of about 800 pounds. However, the increased weight of the AQL and CHAALS systems proved to be problematic. To compound problems, the AQL and CHAALS hardware were engineering development models that had been fully tested. However, additional production units were not yet available.

In response to this situation, the decision was made to initiate production of nine Beech RC-12K aircraft that would include the more powerful PT6A-67 turboprop engines and oversized landing gear. This would provide a maximum takeoff weight of 16,000 pounds, or approximately 1000 pounds more than the RC-12H aircraft. The re-engined RC-12K aircraft would have an operating altitude of 35,000 feet compared to 28,000 feet with the RC-12H. It would have a maximum range of 1,400 nautical miles compared to 1,200 miles with the RC-12H. Like the RC-12H, the RC-12K would have a maximum cruising speed of 265 knots (305 mph), it would have an endurance of 4.5 to 5.5 hours, and could maintain an operating radius of 180 miles between tethered aircraft and the IPF.

Because it would take between 33 and 36 months to complete the aircraft, system integration, and testing, the plan was adopted to modify the original configuration for GR/CS System 3. System 3 would be known as GR/CS (-) and would include a number of the preplanned product improvements, but it would not include CHAALS or AQL. In this way, System 3 could be deployed in Korea in December 1988 to replace the aging GR-V.

Guardrail Common Sensor System 4

Following the deployment of GR/CS System 3, work began on System 4 in late 1988. Because the RC-12K aircraft would not be complete until 1991, a number of pre-planned product improvements were initiated. In addition to the integration of CHAALS and AQL on GR/CS System 4, it would include microwave intercept and downloading frequency intercept extensions, "special" signal receiver capability, expanded multi-channel capacity, Proforma enhancements, and Smart File Cabinet/FasTrack smart map capability. In addition, work continued on SIGINT related software upgrades for processing on combined COMINT/ELINT missions.

In 1989 and 1990, 13 more Beech RC-12K aircraft were ordered. Production of additional AQL and CHAALS units proceeded on schedule and integrated systems tests for GR/CS System 4 were completed successfully. While System 4 was being completed, in late 1989 EW/RSTA began to define the configuration and develop a procurement data package for two additional advanced GR/CS systems. These would be known as System 1 and System 2. These advanced GR/CS systems would replace the older IGRV systems and would incorporate many changes from the System 4 baseline. These would include improved computer systems and display hardware, an enhanced message capability, improved special signal recognition capability, among other improvements. Table 1 presents a comparison of the capabilities of GRV, IGRV, and GR/CS Systems 3, 4, 1, and 2. In addition, Figure 2 presents a summary of the technical evolution of GR/CS.

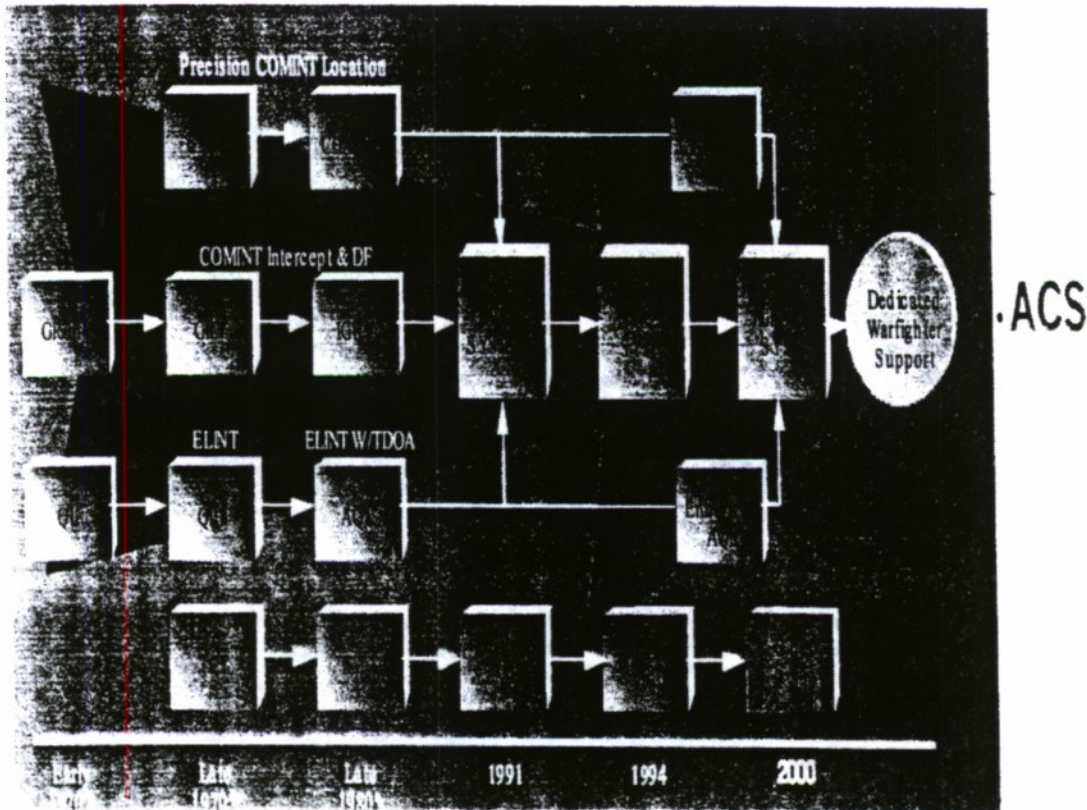


Figure 2 – Common sensor capabilities evolution (Chart, courtesy of TRW)

Capability/Mission Enhancements	GR-V	IGR-V	GR/CS Sys #3	GR/CS Sys #4	GR/CS Sys #1	GR/CS Sys #2	Notes
Universal Workstations	No	No	No	No	Yes	Yes	
Distributed Processing	No	No	No	No	Yes*	Yes	*Has gnd LAN/Workstations
Ada (as dominate language)	No	No	No	No	Yes	Yes	
Scalable configuration	No	No	No	No	Yes*	Yes*	*2,3 or 4 van deployment
Digital terrain mapping	No	No	Yes	Yes	Yes	Yes	
Smart Map/Sensor Mgt	No	No	Yes	Yes	Yes	Yes	
SIGINT overlay	No	No	No	Opt	Opt	Opt	
COMINT	Yes	Yes	Yes	Yes	Yes	Yes	
ELINT	No	No	No	Yes	Yes	Yes	
Receiver pooling	No	No	Yes	Yes	Yes	Yes	
Fast DF/SCARS	No	Yes	Yes	Yes	Yes	Yes*	*Embedded in ATSA
Unified A/B Architecture	No	No	No	No	Opt*	Yes	*Retrofittable
On-board ELINT processing	No	No	No	No	No	Opt	
High resolution DF	No	No	No	Yes	Yes	Yes	
Special signals	No	Yes	Yes	Yes	Yes	Yes	
Number of IPF vans	3	4	4	4	2,3,4	2,3,4	
Number of operators	19	23	26	26	25	26	
Platforms/mission	1,2,3	1,2	1,2	1,2,3	1,2,3	1,2,3	
Platforms, total aircraft	6	6	6	9	12	12	
Reporting	TCT	ICTT	ICTT	CTT*	CTT	CTT-h	*Retrofit
Collateral reporting	No	No	No	Yes*	Yes*	Yes*	*"Air gap" Manual
Interoperability	No	Yes	Yes	Yes	Yes	Yes	
Wideband Microwave link	No	Yes	Yes	Yes	Yes	Yes*	Multi Role Data Link
Separated deployment opt	Yes	No	No	No	Yes	Yes*	*Satellite relay (P3i)
Data Distr System/MLS	No	No	No	Opt*	Yes	Yes	*Retrofit
Programmable payload	No	No	No	No	No*	Yes	*Requires Retrofit
Gateway bridge	No	No	No	No	No*	Yes	*Requires Retrofit
Distr on-board processing	No	No	No	No	No*	Yes	*Requires Retrofit
Receivers per mission	12	28	28	42	42	30*	30 set-on plus 24 WB
Receivers per A/C (Max)	6	14	14	14	14	10*	*10 set-on plus 8 WB
Expanded band covrs	No	No	No	Yes*	Yes	Yes	*QRC expansion
Basic full COMINT coverage	Yes*	Yes	Yes	Yes	Yes	Yes	*Except DF
Extended upward coverage	No	No	No	Yes*	Yes*	Yes*	*Intercept only
Extended downward coverage	No	No	No	Yes*	Yes	Opt	*Intercept only
LPI	No	No	No	Opt	Opt	Yes	
FDDM	Yes	Yes	Yes	Yes*	Yes*	Yes*	*On-board and gnd
PCM/TDM	No	No	No	No	No	Opt	
Proforma	No	Yes	Yes	Yes	Yes	Yes	
SRE	No	No	No	Yes	Opt	Opt	
Signal recogizer on-board	No	No	No	No	Opt	Yes	
DOA DF (multi chan vs 2 chan)	2	2	2	2	2	6	
DF extended coverage, down	No	No	No	No	yes	Opt*	
DF extended coverage, up	No	No	No	no	Opt	Yes	
TDOA (ELINT & COMINT)	No	No	No	Yes	Yes	Yes	
ELINT, basic	No	No	No	Yes	Yes	Yes	
ELINT drop-on covr	No	No	No	No	No*	Opt	*Requires Unified arch
ELINT, Embedded	No	No	No	No	No*	Opt	*Requires Unified arch
ELINT, on-board proc	No	No	No	No	Opt	Opt	
Link, air to gnd	UHF	IDL	IDL	IDL	IDL	GDDL	
Link, air to air	Yes	No	No	No	No	Opt	
Message transponder	TCT	ICTT	ICTT	CTT*	CTT	CTT	*Retrofit
Satellite remotng	Yes	No	No	No	Yes	Opt	
Flight Line Support	AGE	AGE	AGE	AGE	AGE	BH-in*	*Built-in Go, No-go + AGE

Source: Swainston, David. Guardrail Common Sensor Program Summary and System Description, Electronic Warfare, Reconnaissance, Surveillance, and Target Acquisition, CECOM, Fort Monmouth, N.J., 1994.

Table 1 – Guardrail capability evolution matrix

In August 1990, Iraq invaded Kuwait. At this point, it was clear that GR/CS System 4 with its CHAALS and AQL capabilities would not be ready in time for a war with Iraq. System 4 would not be fielded until July of the next year (1991) to the 5th Corps 1st Military Intelligence Airborne Exploitation Battalion at Wiesbaden, Germany. GR/CS System 3 would remain in Korea. America would have to go to war with the two proven IGRV systems and one GRV system that could be deployed in the Persian Gulf.

IGRV and Guardrail V in the Gulf War

Following the invasion of Kuwait by Iraq, in the fall of 1990 the U.S. and its Coalition allies began to prepare for war in the Persian Gulf. By this time, the two Improved Guardrail Vs that had been deployed in Europe had established records of proven performance. As a consequence, the 5th Corps 205th Brigade, 1st Military Intelligence Battalion, moved from Wiesbaden, Germany, the 7th Corps 207th Brigade, 2nd Military Intelligence Battalion moved from Stuttgart, Germany, and the 3rd Corps 504th Brigade, 15th Military Intelligence Battalion (GRV) moved from Fort Hood, Texas to the Persian Gulf.

In the fall of 1990, the two IGRV systems and one GRV system were deployed in Operation Desert Shield to intercept Iraqi communications. As Desert Shield became Operation Desert Storm when Coalition forces invaded Iraq in January 1991, the three Guardrail systems played an important role in intercepting Iraqi military communications.

The Iraqis were well aware of the U.S. COMINT capabilities. David Swainston, former ESL program manager, observed that captured Iraqi soldiers indicated that a high level of awareness existed among the Iraqi troops. This resulted in the fear that radio communications would reveal their position to the Coalition forces. This led in an almost superstitious level of inhibition of communications within the Iraqi army. Thus, the success of Guardrail can be partially attributed to its inhibitory effect on Iraqi communications. This reduced the effectiveness of enemy coordination on the ground.

In actuality, the utilization of the Guardrail systems in the Gulf War was below their potential. First, the GR/CS System 4 with its highly advanced CHAALS and AQL systems was not yet completed and could not be deployed. Second, because the air war was controlled by the Air Force, and Army forces did not begin operations until late in the war, the Guardrail systems never had the opportunity to perform up to their potential with coordinated Army operations. Nonetheless, the role that the Guardrail systems played in the Gulf War cannot be underestimated. They were critical in their role in intercepting Iraqi communications. In addition, their effect on inhibiting ground based communications resulted in the further degradation of coordination among Iraqi troops. Much was learned from the Gulf War experience. From this experience important QRC enhancements were added as improvements to the GR/CS System 3. These included low band intercept, upward frequency extension with programmed multi-channel demodulation, special radio exploitation, and software improvements.

Lesson 1: A High Technology Readiness Level

A number of important factors contributed to the success of the Guardrail program. One of the most significant factors that influenced schedule, budget, and

technical performance in each phase of the Guardrail development was the level of technology readiness. When the program started in the early 1970s, ESL had already developed an extensive base of relevant knowledge among its engineering staff in its laboratories. This knowledge had developed through their experience with ground based remote COMINT systems in Vietnam. In addition, at ESL other DoD programs provided a synergy in the development of the technologies that would be required for Guardrail.

The extensive base of expertise at ESL (and later CHAALS expertise at IBM and AQL expertise at UTL) was only one contributor to the level of technology readiness. Another important contributor was the development strategy that was first instituted at NSA and adopted by ESL, and later adopted by the Army program offices. This development strategy was multidimensional, but one key element was a focus on minimizing technological risk and making design decisions based on technological maturity. However, this strategy included a program of systematic pre-planned product improvements based on technology insertion. The technologies in areas such as integrated circuits, direction location finding technology, signal processing technology, computer hardware and software were evolving rapidly during this period. The Guardrail program offices and ESL believed that as each successive system was completed and fielded, the next system could be incrementally upgraded as a new generation Guardrail system with more advanced technology.

The laboratories at CECOM also played an important role during Guardrail development. George Morris of CECOM noted that in supporting the CHAALS and the Advanced Quicklook programs the CECOM laboratories helped solve numerous technical problems that allowed these systems to mature sufficiently for integration into the Guardrail Common Sensor.

The strategy of minimizing technological risk and making design decisions based on technological maturity worked well throughout the 1970s and 1980s. However, both Charles Dubusky of the Army GR/CS program office and Dave Swainston, retired ESL program manager, believed that the program began to deviate from this strategy in the 1990s. With GR/CS System 2 the technological envelope began to be pushed too far, too soon. This resulted in increased levels of technological risk, and subsequent problems with cost, schedule, and technical performance. This is perhaps a lesson in organizational learning itself. Each successive generation of managers (both government program office and prime contractor) must learn from the successful and failed decisions of preceding programs. In the case of GR/CS System 2, what had been learned in the past in terms of development strategy seems to have been forgotten.

Lesson 2: Utilizing an Open Architecture to Support Pre-Planned Product Improvements Reduced Development Cycle Time

Chuck Dubusky, chief engineer at the government project office, and Herman Redd, ESL field representative, observed that one of the problems projects encounter in areas where the core technologies are advancing rapidly is potential for the system to be obsolete before it is ever fielded. Because Guardrail was becoming increasingly software dependent with each successive generation, to address this problem the Guardrail government program office and ESL instituted two initiatives. The first was the application of real time tactical system processing architecture that was based on the use of international standards and the use of a seven layer Ada protocol. The second

initiative was the Advanced Tactical SIGINT Architecture initiative that employed a unified architecture that was bus oriented and employed all Ada software. Thus, the architecture and the software standards became the basis for the system, not the vintage of computer hardware. As new computer and bus technology was introduced, so would the method of adapting to the established standards. In this way, as computer hardware rapidly evolved, the software for successive generations of Guardrail could be rapidly adapted.

It should also be noted that this approach relied heavily on commercial off the shelf components. In fact, by the time GR/CS System 1 was being produced, of 1176 components, 66 percent were commercial off the shelf. Furthermore, 91 percent were common with other systems. In essence, a key component of the acquisition strategy could be described as evolutionary acquisition. A core capability is fielded with a modular open structure and the provision for future incremental upgrades. Each successive upgrade would then occur as a block of pre-planned product improvements.

Lesson 3: The Use of a Quick Reaction Capability Program When the Fielding Schedule Is Critical

In the context of the Cold War, and under conditions of rapid technological advancements, the normal acquisition processes were viewed to be inadequate by the Guardrail program office. Herman Redd, who worked for the government program office before moving to ESL, indicated that based on the experience of the CEFLY Lancer, program office staff were convinced that a radically different acquisition strategy was needed. This strategy focused on schedule performance and consisted of several important components. First, and most importantly, was the approval of a Quick Reaction Capability program (QRC program). Given the urgent nature of the program, and the fact that top Pentagon officials were convinced of the criticality of the schedule, the program office was able to obtain a letter signed by a four star Army general and a four star admiral (NSA) approving the QRC program. This letter was later referred to as the "eight star letter," and it allowed the program office maximum flexibility to modify and bypass existing acquisition processes.

For example, one of the factors that contributed to the schedule and cost problems with the CEFLY Lancer was the requirement to comply with extensive military specifications (milspecs). Steve Pizzo, an engineering manager with the government program office, observed that the Guardrail program office understood that the great majority of these elaborate specifications would not be critical to Guardrail's performance, however, to comply with such requirements would result in vastly reducing the ability to use existing "off the shelf" equipment and components. This would affect schedule and cost. With the approval of the QRC program, most milspecs were eliminated.

In addition, the program office understood that the standard Army development process with the usual milestones and approvals would reduce their ability to field the system in the time parameters that were needed in the Cold War environment. In light of this, the QRC program allowed Guardrail to be funded almost completely as a production program. In actuality, there was engineering development occurring as the program progressed, but it was funded under the production contracts. In essence, the acquisition strategy was to begin with the baseline Guardrail system and then evolve the system

through blocks of pre-planned product improvements using mature, existing technology. In this way the scheduling ramifications associated with the standard Army acquisition process would be largely bypassed. Of course, such an approach would not be advisable for programs with extensive engineering development requirements or large production runs. In the case of Guardrail, this approach worked because the technology was mature, considerable commercial "off the shelf" equipment could be used, and each system was comparatively unique.

Former ESL Guardrail program manager, Timothy Black, observed another important ramification associated with the use of production contracts. Almost all of the contracts were either fixed price or fixed price plus incentive fee contracts. This forced the contractor to be extremely accurate in cost estimating prior to program start. Because of ESL's depth of expertise in all of the major technologies, cost estimating was generally very accurate.

As noted previously, while engineering development activity was included in the production contracts, it was not funded in the usual way as cost plus incentive fee contracts. Charles Dubusky of the government program office observed that this approach to the acquisition strategy on the part of the government program office resulted in disciplined cost containment.

Lesson 4: When the Schedule for Fielding Is Urgent, the Acquisition Strategy Should Allow for Requirements to Be Set through Dialogue

Steve Pizzo of the Guardrail program office observed that the assumption that competition in defense contracting universally results in superior performance in terms of cost, schedule, and technical performance may be incorrect. Competition should predictably achieve the desired results under most conditions. However, there are conditions under which the normal competitive process in government contracting will not result in the highest level of technical and schedule performance. Guardrail seems to have been one of those programs.

When the schedule for fielding is urgent, the technology is evolving rapidly, and the defense contractor that developed the first (baseline) system is by far the leading firm in terms of relevant system specific technical expertise, then a sole source contract may be required. In the case of Guardrail, the initial contract for Guardrail I was competitive. Thereafter, the contracts were sole source to ESL as prime contractor (with the other pertinent subcontractors). This resulted in several important advantages for schedule and technical performance.

First, the sole source contracts for the sequence of systems following Guardrail I allowed for requirements to be set through dialogue. The usual situation would be for the requirements to be specified prior to a request for proposals (RFP). Thus, requirements would be set in advance. In the case of Guardrail, ESL engineers and government engineers worked very closely to develop specifications for each successive system within the general requirements specified by TRADOC. However, TRADOC generally deferred to the judgment of the program office, and this allowed for specifications to be developed through joint dialogue between engineers at ESL and the government.

Ron Ohlfs, former chief systems engineer at ESL, suggested that this approval worked well because ESL could effectively identify requirements that might not be cost

effective or requirements that could adversely affect the schedule. Thus, the dialogue tended to influence the process so that design decisions approached the optimum.

Both George Morris of CECOM and David Swainston concluded that TRADOC contributed to the requirements stability and funding stability of the program. This was very advantageous to Guardrail because it allowed the engineers to work in an environment that minimized dysfunctional change. When changes or new capabilities were presented by TRADOC, the Guardrail program office would assess the technical feasibility and cost implications and introduce the change in the next successive generation of pre-planned product improvements. However, TRADOC basically deferred to the judgment of the technical experts at CECOM and ESL as to what was and was not cost effective or technically feasible. In this way, the program benefited from an environment of stability.

Lesson 5: Achieving Effective Integration for the Common Sensor: A Central Challenge for the Program Managers

From the beginning of the Guardrail program, internal integration at ESL had been managed very effectively. ESL had utilized a project-matrix structure with a functional engineering organization. The functional areas included laboratories, and the organization was based on engineering specializations. The Guardrail program office obtained engineers from the various functional areas. These assignments were typically full time until an individual was reassigned to another project. In addition, the laboratories or functional groups would provide technical support to the Guardrail program office on a task by task basis.

The program office had a team of assistant program managers that each managed a major subsystem or functional area. One of the former ESL program managers, Timothy Black, indicated that the team of assistant program managers met on a near daily basis because of the high degree of interdependency among the various systems. To keep the program on schedule, PERT (program evaluation and review technique) was used extensively, and schedules were reviewed weekly on a task by task basis. Even before concurrent engineering became common, ESL was applying the basic processes in the Guardrail program.

Prior to Common Sensor, external coordination with the various subcontractors was minimally complex. As prime contractor, ESL assumed responsibility for system integration. With the advent of the Common Sensor and the addition of the CHAALS and AQL systems, integration increased in complexity. ESL and the Guardrail program office at Ft. Monmouth developed interface control documents to specify the necessary interfaces with equipment being developed and produced by IBM, ESCO, Beech, Unisys, UTL and other contractors.

Steve Pizzo and George Morris on the government side and Tim Black on the contractor side observed that the interface between ESL and the government program office was much like an integrated product team (IPT). Long before these came into vogue in the 1990s, ESL and the Guardrail program office were implementing this type of interorganizational project coordination. George Morris observed that when IPTs were formally implemented in the 1990s, they tended to be leaderless groups and decisions tended to be reached by consensus. In some instances this worked well, but in other cases the consensual decision making simply did not work. Morris noted that in the

1980s, prior to the formal implementation of IPTs, in the Guardrail program the interorganizational teams were not leaderless. Typically the final decision authority on any matter was retained by the government program office. However, as a general practice, there was deference to the judgment of those who had the greatest technical knowledge on a particular matter. This approach seemed to work more effectively than the leaderless IPT approach.

In general, the government program office and ESL effectively managed the system integration. However, there was one significant exception. This was the management of the weight for the Beech aircraft during GR/CS System 3. This was a miscalculation that Beech, ESL and the Guardrail program office did not discover until System 3 was being tested. This miscalculation resulted in the need to re-engine the aircraft, and this led to serious delays in the completion and fielding of GR/CS System 3.

The problem could have been avoided if Beech, ESL, the other contractors, and the Guardrail program office had been adequately monitoring the weight problem. If discovered earlier, the replacement of engines on the Beech aircraft could have then occurred concurrently so that the original schedule could have been achieved.

In any case, George Morris of CECOM concluded that integration is facilitated when there is a single prime contractor with multiple subcontractors, and the prime contractor assumes total responsibility for integration. As Guardrail moved into the Common Sensor program, the CHAALS and AQL systems were furnished to ESL through the government program office as government furnished equipment (GFE). ESL had responsibility for integration, but the relationships were ostensibly different because IBM was not a subcontractor to ESL for CHAALS. Neither were UTL or ESCO subcontractors to ESL for AQL.

Like Morris, Steve Pizzo of the Guardrail program office observed that systems with multiple prime contractors have more complex integration problems. Just as the Navy Battle Group Passive Horizon Extension System (BGPHEs) suffered from extensive integration difficulties due to multiple government project offices with multiple prime contractors, as GR/CS began to move in a similar direction, integration became increasingly problematic.

Lesson 6: A Corporate Culture Can Affect the Success of a Program

Given the large learning curves associated with system specific technical knowledge on complex defense systems, continuity in personnel can be a very important contributor to performance. This is not to say that a continuous infusion of new talent is not necessary. This too is essential to any engineering organization. However, managing turnover and retention is clearly a problem of optimization.

Tim Black and David Swainston observed that at ESL a core group of engineers worked on the program for a number of years. In fact, as many as 100 engineers worked on the Guardrail program at ESL for a duration of 15 years. Since each Guardrail program was successive, there were no gaps in time where a large amount of turnover and new hiring had to occur. This continuity clearly facilitated organizational learning and the enhancement of the extraordinary base of expertise at ESL.

Tim Black and Ron Ohlfs suggested that several important factors contributed to ESL's ability to retain such a talented cadre of engineers. First, ESL was very competitive in terms of salary and benefits. This allowed the TRW division to attract and retain highly talented individuals. Secondly, the corporate culture created an environment that made ESL a very collegial and enjoyable place to work. From the very beginning, William Perry (who would later become Secretary of Defense) tried to create a very close knit, cohesive climate at ESL. Even as the company grew larger and became a division of TRW, ESL still maintained a highly cohesive and supportive culture.

A third factor that characterized ESL was a corporate culture that emphasized flexibility. To illustrate, in the late 1970s Ron Ohlfs had considered leaving ESL. His reasoning was based on the fact that he was spending an inordinate amount of time on functional management tasks, and he missed spending the larger proportion of his time on purely technical work. He discussed his sense of diminishing job fulfillment in terms of functional management responsibilities with his program manager. The program manager then approached the president of ESL, Don Jacobs, about the situation. Jacobs' response was characteristically atypical. He simply said that ESL needed to create a work environment where talented and self motivated people are free to do what they do best. As a consequence, the company introduced a type of a dual career ladder where exceptional engineers could progress in a technical track and provide technical leadership in the company without being burdened with managerial responsibility. As a consequence, Ohlfs stayed another 15 years.

A fourth and perhaps most important factor that contributed to retention was that the engineers working on the Guardrail program had a collective vision for where the technology could eventually go. Furthermore, they understood the national importance of their work in the context of the ominous threat of the former Soviet Union. The combination of these important factors contributed to the continuity in the base of expertise that was successfully maintained at ESL.

Conclusion

The historical development of the Guardrail program summarized in this case suggests that this evolution of advanced airborne communications and electronic intelligence systems represented one of the most successful defense systems developed during the last third of the twentieth century. Based on measures of program cost, schedule, and technical performance, the sequence of Guardrail systems was exceptional. The Guardrail systems provided commanders in the field with critical information during the Cold War, Desert Storm, and the conflict in Central Europe.

As the program moves into the twenty-first century, the COMINT and ELINT capabilities will be adjoined with imagery intelligence (IMINT) and measurement signature intelligence (MASINT) capabilities. This will be the next step in the relentless succession of Guardrail systems and it will be called the Aerial Common Sensor. The Aerial Common Sensor is scheduled to be deployed in 2010, and it is a system that stands on the shoulders of giants when one views its extraordinary technological heritage.

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AGM – 114 HELLFIRE

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Editors' Note

In contrast to the other case studies included in this report, the focus of much of the discussion which follows is on a single important subsystem of the HELLFIRE missile system. The author found the development history of the laser seeker to be particularly interesting and chose to write mostly about it, dealing with the rest of the system only in passing.

Introduction

HELLFIRE, short for **H**elicopter **L**auncher **F**ire and **F**orget **M**issile, is a modular missile system designed to destroy tanks and other armored targets through the use of a shaped charge warhead. It is guided to the target by a semi-active laser seeker which homes on the energy reflected from a target which has been illuminated by a laser designator. This designator may be located on board the same helicopter as the HELLFIRE, on another airborne platform, or on the ground, in either vehicle-mounted or man-carried configurations. The figure below shows the key elements of the missile.

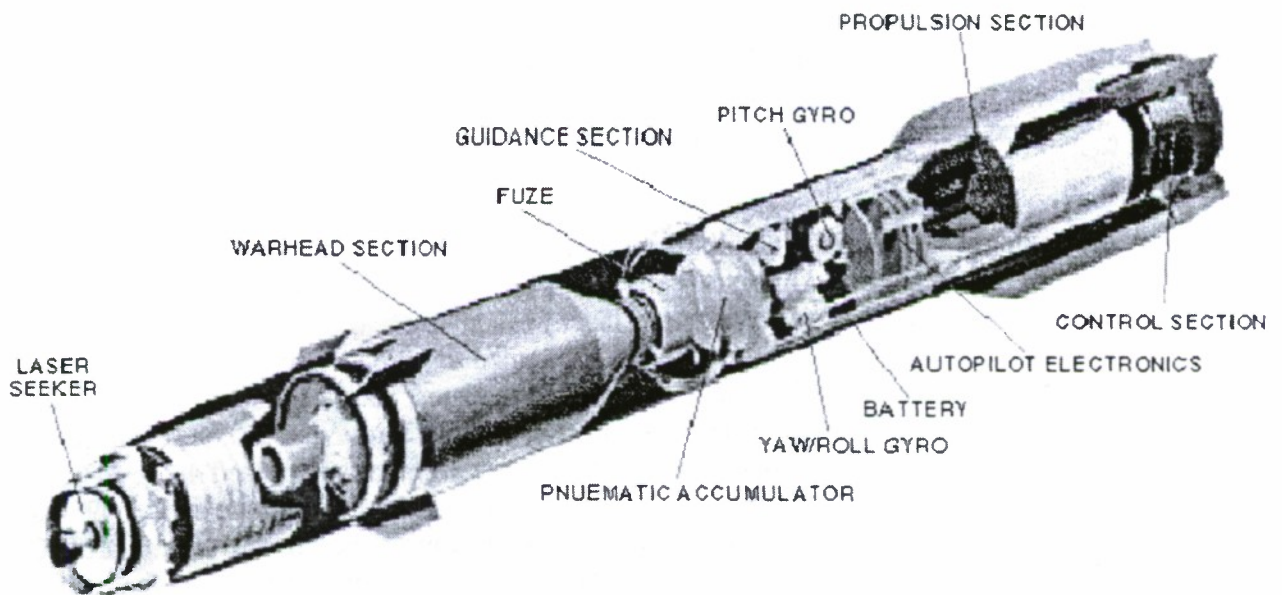


Figure 1.- HELLFIRE Missile (AGM-114)

While HELLFIRE was first employed operationally (and successfully) in Operation Just Cause in Panama, it received world attention as it saw extensive use in Desert Storm. Perhaps its best publicized use in Desert Storm was to suppress Iraqi air defense radars during the first hours of the war, thus allowing essentially undefended access for the Coalition air forces to attack key targets throughout the country. Ironically, HELLFIRE's inherent air defense suppression capability had been deliberately deemphasized during development, in order to concentrate on the more critical anti-armor capability.

When fielded, HELLFIRE was the latest in a series of air-launched anti-armor systems which had been developed by the contractors involved. There were several common technological threads running through these various system developments, extending

back to developments made by German missile scientists and engineers during World War II. A brief summary of some of these systems will be found in the Appendix.

Laser Seeker Beginnings

The technology for the Hellfire seeker was an outgrowth of the pioneering laser research done by David Salonimer at Redstone Arsenal, AL in 1962, after engineers at the Army Missile Laboratory began developing a concept of semi-active guidance in 1961. A laser was one of several potential energy sources documented in an early semi-active guidance patent. It was recognized early on that any laser illuminator used as a man-portable target designator could weigh no more than about 40 pounds. However, the initial concept to illuminate the target with a continuous laser beam would consume far too much power to fit under such a weight constraint. Mr. Salonimer proposed pulsing the laser in short bursts. Mathematical modeling showed that this idea would work. In addition to using target designators operated by forward observers, Mr. Salonimer also suggested the idea of using an airborne laser to illuminate the target.

Soon the investigators became so interested in the potential of this research that they sought developmental confirmation. In 1963 the U.S. Army Missile Command (MICOM, the Missile Laboratory's parent) let small contracts to Rockwell's Autonetics Division and to RCA to investigate laser seeker approaches. The Autonetics approach was aimed at anti-armor use, while RCA planned to guide a surface-to-surface "artillery" missile. In six months both had demonstrated their respective concepts in the laboratory – Autonetics using solid-state devices, and RCA using a television tube technique. At the same time Autonetics had developed their own lightweight pulsed laser to use as an illuminator. The focus of the work then shifted to prototype hardware and in 1964 awards were made to several firms to investigate other approaches to the illuminator. One of them, Martin-Marietta, was able to deliver a pulsed illuminator at less than 40 pounds weight. By the end of the year testing (on a high speed sled simulating the terminal stages of missile flight) of the Autonetics seeker had begun and Martin-Marietta's ground illuminator was nearing delivery. MICOM also arranged with Texas Instruments in mid-1964 to use their Shrike missile as a low cost demonstrator for the new seeker. In May 1965 the Air Force formally asked MICOM to investigate laser guided bombs. Within a year Rockwell International and Texas Instruments offered proposals for a production bomb. With MICOM technical personnel providing key support in design evaluation and subsequent development, Texas Instruments won the bomb seeker competition and Martin-Marietta developed the aircraft mounted illuminators for the Air Force. Thus, the first operational use of semi-active laser guidance occurred during the Vietnam War for the attack of high value fixed targets such as bridges.

The Army realized early-on that data was needed to assess the utility of conceptual laser guided weapons when employed in realistic battlefield environments. In mid Fiscal Year 1971 the Army established the Laser Terminal Homing Measurements Program. This program was conducted primarily by in-house Army Missile Laboratory personnel

to define the operational environment, conduct laboratory and field measurements of target signatures, and to develop computer models to conduct systems analyses and simulations. A Terminal Homing Data Bank was established at the Redstone Scientific Information Center (RSIC), as a repository for signature measurements. This data bank later served as the nucleus of the DoD Tactical Weapons Guidance & Control Information and Analysis Center. Additionally, RSIC established a program known as Tactical Operations Assessment to obtain real world data on the characteristics of various tactical environments, with emphasis on smoke, dust, and other battlefield conditions that may degrade the performance of laser-guided missile systems. The results of this measurements program were used by the initial HELLFIRE program manager to answer critical questions on the utility of such a system.

HELLFIRE System Development

Official development of HELLFIRE began on December 11, 1972 when MICOM established a dedicated project office, with COL John Hanby as the Project Manager. The Army offered HELLFIRE for use by the other U.S. military services ("tri-service" use) in 1973. A full chronology on HELLFIRE can be found in Table 1.

Tri-Service Seeker

At first, since Hellfire had been offered for tri-service use, a multi-purpose seeker was desired which would serve the needs of the Army, Navy (Marines), and the Air Force. However, each service had its own idea as to the form the seeker should take. Both the Army and the Marines were leaning towards a laser system with a ground-based target designator to be used by a soldier operating much like an artillery forward observer. The Air Force was interested in a laser seeker as an interim solution for Maverick, better than the existing day-only electro-optical (TV) seeker, but to be ultimately replaced by a more capable fire and forget imaging infrared seeker. Initially, the Department of Defense gave the Air Force the role as the prime development manager for the tri-service laser seeker (TLS) since they had a program in place (Laser Maverick) and it was still unsure whether the next-generation Army attack helicopter would see a go-ahead (and particularly whether HELLFIRE would be chosen as its armament over the existing TOW). As it turned out, there were schedule delays for Laser Maverick (believed by some to have been caused by the need to keep the Maverick production line active while awaiting the next-generation fire-and-forget IR seeker) and that there never was a serious Air Force operator interest in a semi-active laser guided system that required an expensive airborne designator to "hang around" in a severe threat environment.

Thus a situation arose where the Air Force was responsible for developing a seeker (the TLS) that they really didn't need, and Army (after getting the Apache go-ahead in November 1976) was in serious need of laser seekers they really preferred to meet just their specific requirements (that is, without some of the countermeasure defeating complexities and other technical limitations associated with the Air Force mission).

<u>Date</u>	<u>Event</u>
1971	Army established program titled "Heliborne, Laser, Fire and Forget Missile" to start in 1972. Program name subsequently changed to Helicopter Launched Fire and Forget Missile (HELLFIRE)
Feb 1972	Congress released HELLFIRE funds; requirement for military potential test was included
Apr 1972	Contracts were awarded to Hughes Aircraft and International Laser systems for prototype ground laser designators which could be used to acquire targets for HELLFIRE (and similar laser-guided systems)
Oct 1972	The Army Missile Lab evaluated competing seeker technologies for HELLFIRE in tests at Eglin Air Force Base, FL
Dec 1972	HELLFIRE Project Office established as an element of the U.S. Army Missile Command, Redstone Arsenal, AL
Apr 1973	Contracts were awarded to Bell Aerospace and Philco Ford for prototype airborne laser designators which could be used to acquire targets for HELLFIRE (and similar laser-guided systems).
1973	Army offered HELLFIRE for tri-service use
Dec 1973	Army reoriented HELLFIRE to advanced development to resolve operational uncertainties and directed operational tests be done
Jun 1974	Rockwell International and Hughes Aircraft awarded contracts for development of prototype (advanced development) HELLFIREs
Jan 1975	Army directed HELLFIRE development to focus on anti-armor role; no funding to be expended on air defense suppression capability
Mar 1975	Air Force, as executive agent for HELLFIRE laser seeker development, awarded contract to Rockwell International for seeker development
Mar 1976	Deputy Secretary of Defense authorized engineering development of HELLFIRE
Oct 1976	Rockwell International awarded HELLFIRE engineering development contract
Oct 1976	Airborne laser designator replaced with the Target Acquisition Designation System, developed by the U.S. Army Aviation R&D Command
Oct 1976	Army Missile Lab tasked to develop high fidelity simulation to link laser designator performance to missile probability of target hit
Nov 1976	Deputy Secretary of Defense approved HELLFIRE as point target attack subsystem for the Advanced Attack Helicopter (subsequently AH-64, APACHE)
Sep 1977	Martin-Marietta awarded contract for low cost alternative laser seeker (LOCALS)
Dec 1978	Martin-Marietta's LOCALS selected as HELLFIRE seeker
Apr-Jun 1980	Operational tests of HELLFIRE conducted at Fort Hunter-Liggett, CA
Feb 1982	Martin-Marietta awarded production contract for HELLFIRE laser seekers
Mar 1982	Rockwell International awarded production contract for HELLFIRE missiles and launchers
Apr 1986	HELLFIRE approved for use with APACHE helicopter (AH-64) and fielded in consort with APACHE fielding schedule
Dec 1989	APACHes fired seven HELLFIREs during Operation Just Cause in Panama; all were direct hits

Table 1 – HELLFIRE Chronology

According to the HELLFIRE Army Project Manager at the time, COL Robert Feist, the tri-service effort became no longer viable when the Air Force decided not to use the laser seeker for Maverick, but to go straight to an infrared imaging seeker instead. TLS development continued for a while, but projected costs increased to three times their original level. After many briefings to senior decision makers, permission was granted for a parallel development, managed by the Army, of a HELLFIRE seeker alternative to the tri-service seeker.

Low Cost Alternate Laser Seeker (LOCALS)

This Army-managed seeker development became known as LOCALS. There were many potential applications for HELLFIRE at the time, but according to COL Feist, the Army leadership felt that having the anti-armor HELLFIRE capability greatly strengthened the justification for developing the Apache helicopter as a replacement for the Cobra. Therefore, he wasn't allowed to pursue any other applications (and developments), such as the ground-based launch system the Marines wanted or the air defense suppression version mentioned in Table 1. (Author's note: Subsequently, ground-launched versions of HELLFIRE were developed by Rockwell for sale to foreign governments.)

In 1976 an engineering development contract competition was conducted (in which Martin-Marietta was a losing bidder), with Rockwell International being chosen to develop the HELLFIRE missile system (the missile "bus" and launcher, as well as the missile seeker). Initial seeker requirements were primarily determined by the highly maneuverable HELLFIRE system.

Rockwell soon had problems with the sensitivity/complexity of their seeker design (the TLS) and began falling behind schedule. This inevitably resulted in their advising the government project manager of a very unwelcome increase in program cost.

With funding from a Department of Defense program entitled Manufacturing Methods and Techniques (MM&T), the Army Missile Laboratory had contracted with Teledyne Brown Engineering to take a somewhat different approach to the design of a laser seeker. Teledyne Brown was to systematically analyze the seeker requirements and features which made a laser seeker (of the class of SIDEWINDER-like spinning mass seekers) difficult and expensive to manufacture and to optimize the seeker design for production. Many of the results of this work were subsequently incorporated into the HELLFIRE laser seeker.

At about the time that Rockwell's seeker was experiencing development problems, the HELLFIRE Project Office and the Army Missile Laboratory became aware that Martin-Marietta was learning things on the development of COPPERHEAD (a laser-guided

artillery shell) which might benefit them. They asked questions and awarded a small (~\$100,000) study contract to Martin-Marietta. This brief study indicated that there was potential for "commonality"; in that some of the electronics technology used in the COPPERHEAD seeker might apply to a HELLFIRE seeker. In effect, Martin-Marietta said they could supply an alternate seeker to the one under development by Rockwell.

With the problems that Rockwell was having and the program risk this created, the Martin-Marietta proposal was greeted with a positive response from MICOM. In April 1976 an initial letter contract was written and Martin-Marietta subsequently negotiated a contract for \$10.2 million to develop a low cost seeker. Rockwell was also awarded an additional \$5 million contract to modify the TLS design to reduce its cost. The production cost reduction design approaches developed by Teledyne Brown Engineering in the MM&T program were made available to both Martin-Marietta and Rockwell. The Army's plan was to run both contractors in a head to head competition and give the majority of the seeker work to the winner.

Borrowing parts from COPPERHEAD seekers and drawing heavily from the MM&T seeker design, Martin-Marietta was able to deliver some potential HELLFIRE seekers to MICOM's Missile Laboratory, where they were tested. The end result (in late 1978) of the competition was that Martin-Marietta's design was chosen as the HELLFIRE seeker and Rockwell's contract was canceled. The seeker name was changed from LOCALS to HELLFIRE Laser Seeker.

A number of Autonetics (Rockwell) TLS systems were provided for early HELLFIRE development. These systems were fully characterized in Rockwell's Hardware-in-the-Loop (HWIL) facility in Columbus. This HWIL facility was designed around a high performance three-degree-of-freedom motion table to simulate trajectory flight with a mounted seeker viewing a rear-projection screen through a large collimator lens, on which a true target laser spot was presented. Two ND:YAG lasers were used to generate the true target and false return laser spots, driven by two-axis steering commands from the HWIL trajectory simulation, or by an external source used for seeker characterization tests. The energy and spot-size of the two laser spots was varied to represent range closure effects. The laser energy dynamic range matched the 8 orders-of-magnitude encountered in realistic operational conditions. (A similar system was later constructed at the Army Missile Laboratory using the Rockwell-developed technology.)

The HWIL facility was used extensively to characterize the TLS seeker performance and to validate the computer simulation model of the HELLFIRE system. Each seeker was fully characterized for model validation and then subjected to extensive pre-launch HWIL trajectory flyout verification for its intended launch. All these data proved invaluable in conducting post-flight analyses, especially in the early development flights.

After several HELLFIRE development flights, the first LOCALS seeker was produced by Martin-Marietta and then provided to Rockwell for evaluation. One condition was

that Rockwell could not disassemble the unit - it was provided for assessment as a "black box" with only the electrical connector available for use for probing. No internal design or implementation details were provided, therefore all the physical and functional characteristics needed to be derived through hardware testing. These characterization tests proved very valuable in finding a number of problems with the LOCALS seeker design. While initially the results of these Rockwell tests were viewed with suspicion, they were all repeated and reviewed, and found to identify valid concerns. Over the next few years, MICOM, Martin-Marietta and Rockwell worked together (albeit reluctantly at first) to work through all these issues, resulting in the development of an outstanding laser seeker and a very effective missile system. They even successfully converted the design documentation to metric units prior to production.

In fact, the government Project Manager identified the amount of effort that had to be invested in managing the often adversarial relationship which existed between the seeker contractor (Martin-Marietta) and the systems integration contractor (Rockwell) as the most difficult problem he faced. For a considerable period it was rare to have a meeting involving the two contractors and the Project Office that was not well attended by lawyers and contracting people from each contractor.

The high fidelity analysis of HELLFIRE and other semi-active laser (SAL) systems performance in smoke/obscurants did not occur until after the government in-house development of the Battlefield Environment Laser Designator Weapon System Simulation (BEWSS) in the late 70's. This activity was a follow-on to the Army's Laser Terminal Homing Measurements Program. Additionally, a series of smoke/obscurant field tests, sponsored by the Project Manager, Smoke, and conducted annually for a period of approximately 13 years, evaluated the performance of SAL seekers such as HELLFIRE and COPPERHEAD, and collected SAL performance data, in addition to measured smoke parameters (particle size, number density, etc.) for a family of domestic, foreign, and developmental obscurants. This data was used to validate the BEWSS model's results against real-world field test data obtained on the sensors. These annual "Smoke Week" exercises, over the years, served to continually update and validate the BEWSS simulation. BEWSS ultimately became the paramount modeling and simulation tool used to assist in the achievement of HELLFIRE milestones.

HELLFIRE's "Technology Transfer" Strategy

Although the Army's decision to bring another laser seeker into the picture played a role in the program's success, that role was more than helping to reduce risk in meeting the technical requirements of the weapon system. It ultimately provided an effective way for the Army to have a competitive production environment.

Initial contracts to build HELLFIRE after development were small, with only a little over 600 missiles made. Martin-Marietta furnished seekers, and Rockwell furnished the rest of the missile. Then for the second missile buy cycle the Army decided that there

should be competition. Rockwell and Martin-Marietta were both given in effect an "educational" buy of 1000 HELLFIREs and told to teach each other how each one's portion of the total system was manufactured. This "technology transfer" strategy was viewed with less than wild enthusiasm by the contractors. Martin-Marietta managers contacted General Dynamics staff members, who had had a similar experience with McDonnell Douglas on Tomahawk, and spoke to a manager who had been involved with that program. He said that the first thing he could tell Martin was "if you don't have to do it – don't!"

Martin-Marietta managers remembered that it was an unnatural experience. It was like being told by the customer that we want you to get married, live together, and teach each other what you do – and then four months later we want you to divorce and compete. And it worked, at least from the Government point of view.

Missile buy cycle three was the first competitive buy, with the winner able to produce as much as 60% of the total, depending on the attractiveness of his price. Martin-Marietta got 43% and Rockwell 57%. In missile buy cycle four Martin-Marietta won 71%. In missile buy cycle five the Martin-Marietta managers thought they made the best bid they could at around \$28,000 to \$30,000, but Rockwell won the maximum share of the production (75%) with a bid of \$23,500 per missile. This pattern continued in the succeeding buy cycles, with Rockwell and Martin-Marietta alternating winning the majority share, with the missile price typically about \$25,000.

The Government got a high quality product at a far lower price than it might have otherwise. Obviously, creative structuring of the production contract is required to make this approach practical. For example, each contractor received incentives (i.e. greater profit) in their contracts, depending on how well the other contractor performed.



Figure 2 – APACHE (AH-64) firing HELLFIRE

Programmatic Lessons Learned on HELLFIRE

- 1) It required a fully committed development management team – both contractor and PMO. Rockwell made a corporate commitment very early in time to winning the Army's next anti-tank weapon program (after TOW). That involved extensive IR&D and marketing funds from the very beginning of the THFTV program to support the program both technologically and politically. That included 6 degrees-of-freedom modeling and simulation, autopilot and flight control definition and design, missile physical configuration trade-offs and a significant number of white papers provided to congressional staffers. One of the biggest contributions made by Rockwell was the Force-on-Force operations analysis to show the cost effectiveness of Hellfire over TOW against the ZSU-23. This helped to clearly establish the case for HELLFIRE as missile armament for APACHE.
- 2) It required a highly skilled and mutually respectful technical development team – contractor and government labs and PMO. The Rockwell HELLFIRE technical staff began working on HELLFIRE when it was the internally-funded terminal homing flight test vehicle (THFTV) program and continued into and through the government-managed HELLFIRE engineering development program. They had already built a significant number of six-inch and seven-inch diameter laser guided missiles which had been successfully launched from AH1 Cobra helicopters against both billboard and tank targets. Each launch was preceded by a hardware-in-the-loop simulation of the actual launch parameters using the hardware to be launched. There was technical and management continuity at Rockwell from THFTV through the advanced development (THAD) program to HELLFIRE. The same is true of the Army Missile Laboratory staff. The technical relationships and respect between the government laboratory and Rockwell staffs developed over a period of four to five years, including successes and setbacks. In addition, the experience of several key members of the HELLFIRE government Project Office staff during their earlier involvement with TOW missile development brought a philosophy of requiring solid systems/concurrent engineering and then conducting tests, tests and more tests during development to assure that the product delivered to the operational units functioned.
- 3) It required early and significant involvement of the Army operational community (the "User"). From the very beginning, strong ties to the operational units were established to conceptualize tactics and understand logistical requirements. Cobra helicopter pilots with operational experience made up the THFTV, THAD and HELLFIRE development launch crews and had extensive input to the launch planning and after launch test reports. TRADOC was kept apprised of the progress of the early launch results and missile characteristics. These contacts proved invaluable as the program moved forward.

- 4) It required a vision for the future. The need for a modular missile design which would accommodate a variety of interchangeable propulsion, warhead and seeker subassemblies, without redesigning the entire missile, was incorporated very early into the system concept. This decision has made the HELLFIRE missile design flexible enough to be used in a number of applications for a variety of users, both foreign and domestic. The useful lifetime of the basic missile has been extended well beyond what could have been expected in 1976 at the start of engineering development.
- 5) The HELLFIRE story provides an interesting example of the dynamics which occur when government researchers invent an important technology. When this happens the involved technology is not held as a proprietary secret. After initial development, it is available to companies interested in further developing it through technology transfer. Commercial companies will fund internal research projects which show some possibility of immediate profit. Scientists and engineers at government laboratories don't need to concern themselves with a technology's profit potential, only the potential application to government needs. The skills and knowledge they develop become part of a technology base shared with others; the availability of this know how to pertinent projects can have far reaching effects. This turned out to be the case with the development of the semi-active laser technology that was the basis for HELLFIRE's seeker.

Other Lessons

The story of HELLFIRE is important for the details of its technological development, and for the lessons learned during its evolution and use in combat. HELLFIRE was a key contributor to the Coalition success in Operation DESERT STORM, beginning with the knock out of air defense systems on the first day of conflict. The lessons have implications for future project developments and military policy. It has taught not only us, but also others the value of technologically advanced precision-guided weapons.

A member of the Foreign Military Studies office at Fort Leavenworth, Kansas, Major Gilberto Villahermosa, U.S. Army, has written an excellent review of Soviet thoughts and beliefs in "DESERT STORM: The Soviet View". He found that Soviet reaction was almost immediate with comment from a variety of high-level sources. The wide variety of seesawing reactions showed confusion and disbelief as to what had really happened. Some accepted the allied successes, while many others could not believe that an armed force equipped with Soviet equipment, and with a large number of officers and soldiers trained by the Soviets could fail so miserably. Opinions were offered that while there was some degree of initial surprise and success, the war could drag on.

On January 19, two days after the initial Radar sites had been destroyed by HELLFIREs launched from AH-64 APACHES, Major General Zhivits of the USSR

Armed Forces General Staff Center for Operations and Strategic Studies warned Soviet readers, in an interview in Izvestiya, not to overestimate allied successes.

On January 21, Lieutenant General Gorbachev, Faculty Chief at the General Staff Academy (equivalent to the U.S. War College) concluded that the outcome of the war had been determined in its first minutes.

A few weeks later, on February 6th Colonel V. Demidenko, a Soviet Air Force pilot, stated that allied claims to have destroyed up to 70% of the Iraqi Air Force were a "propaganda bluff".

At about the same time, in the wake of the Iraqi defeat, The Soviet Minister of Defense was said to have admitted to "weak spots" in Soviet air defense systems, and that Allied successes were under review by the MoD. That public admission must have been like pulling teeth without anesthetic, and could have indicated serious intent to revamp systems design and deployment, as well as training programs.

As the reality of the situation began to sink in, authoritative and experienced hands began to weigh in. Marshall of the Soviet Union Victor Kulikov, former Commander-in-Chief of Warsaw Pact Forces said "A deeper analysis is necessary, but one point is already clear; The Soviet Armed Forces will have to take a closer look at the quality of their weapons, their equipment, and their strategy."

The summary analysis of Major Villahermosa's report was by Colonel David M. Glantz. He concluded: "Soviet anxiety over the poor performance of specific Soviet weapons and integrated systems will pale beside their realization that modern high-precision weaponry, artfully and extensively applied, produced paralysis and defeat." This is indicative of the fact that U.S. weapons development policy and practice must not become complacent with successful implementations such as in DESERT STORM. Soviet (now Russian) response to our performance will likely develop ways to defeat the superiority in the field that HELLFIRE gives us, once they are willing to admit that their previous methods had deficiencies. We must continue to explore all avenues towards **continued** excellence, and toward retaining what we learn from lessons in systems like HELLFIRE if we hope to maintain our lead over current and future opponents.

APPENDIX: (SELECTED) HISTORY OF GUIDED ANTI-ARMOR MISSILES

The contractors primarily involved in HELLFIRE, Martin Marietta and Rockwell, had access to a knowledge base that was built over a long period of technological development and project success beginning as early as 1954. Some examples of successful developments in the area of precision guided missiles and related weapons date from even earlier. This experience is summarized in the paragraphs which follow.

Early Efforts – Germany

During WW II, reeling from attacks on the Eastern front by massive Soviets tank forces in 1944, Germany began several crash programs to develop easily fielded and operated systems. Only one of them made good progress, the X-7 from Ruhrstahl, drawing upon prior experience with the wire-guided X-4 AAM. The X-7 (named “Rotkppchen” or Red Riding Hood) was particularly effective against even the heaviest armor, though only a few hundred were thought to have reached troops in the field. It began as a strictly joystick controlled wire guided missile (much as FOG-M was in the US during the 1980’s and 1990’s with fiber optics instead of wires), with later variants such as the Steinbock (Capricorn) having automatic infrared homing (like Maverick). The Peifenkopf (Pipe Bowl) and Pinsel (Paint Brush) were electro-optical guided, with at one of them having a spiral scan television head able to detect the optical contrast of the target against the background. Similar television guided missiles did not appear in US inventories until the 1960’s, although there was work on television-guided glide bombs during WW II. Later that year (1944) BMW produced its own anti-tank missile that resembled the X-4 AAM with a derivative intended for air launch against hard targets, in much the same way that Hellfire was initially used in Operation Desert Storm against Iraqi radar sites.

USA – Bullpup

In the first decade after WW II the US developed several anti-armor systems, later grouped under the air-to-ground category. One of the first was the Bullpup, designed for the US Navy during the Korean War. Too late for the conflict, it was contracted to Martin-Marietta in May 1954. Similar to WW II German weapons, it was air launched and guided to its target via a radio control joystick. The Bullpup and its variants were kept in production until 1970 with a total of 22,100 being made. A final test variant labeled Bulldog was designed in a partnership between Texas Instruments and Martin-Marietta at the Navy’s China Lake facilities, which equipped it with a laser guidance system. Bulldog saw testing in the early 1970’s with final approval for service use in 1974 – but was canceled in favor of the Maverick, which saw effective service with Israel during the 1973 Yom Kippur War.

Maverick

AGM-65 Maverick was initially approved for development in 1965. Production was awarded to Hughes in June 1968 after competition with Rockwell, who had perhaps hoped to leverage off of their experience with Hornet. The initial AGM-65A saw production of over 17,000 units, and by 1978 initial testing had been completed on the laser guided AGM-65C. This model used the tri-service laser seeker originally designed for HELLFIRE, but saw minimal production and deployment

Copperhead

At roughly the same time as the development of the laser guided Maverick and the development of the aborted laser guided Bulldog was the development of the Cannon Launched Guided Projectile (CLGP) at Rodman Labs, Rock Island Arsenal. The CLGP was to be a laser guided 155mm Howitzer round, later tested by MICOM at Redstone Arsenal, AL With the seeker under contract to Martin Marietta, successful tests were performed as early as October 1975. With an initial production contract in 1979, it entered service in the mid 1980's. Some of its seeker technology was applied from its work on CASM (Close Air Support Missile).

Hornet

North American Rockwell's Autonetics Division (later part of Rockwell International) began a technology demonstrator designated as AGM-64 Hornet from 1963 to 1966 to investigate the feasibility of homing systems against armor on the battlefield. Hornet was normally guided by a stabilized television guidance system, which locked on prior to launch and allowed homing without further control from the launch aircraft. (this was the beginning of the concept of "Lock-on-before-launch") Hoping to capitalize on their Hornet experience, in 1965 Rockwell bid on development work for the Maverick. By 1968 they had lost out to Hughes Aircraft for the Maverick production contract. However, their experience was of use to them in 1970 when the Hornet was used as the Terminal Homing Flight Test Vehicle (THFTV) for development of seekers for the next generation of anti-tank missiles. These tests can be considered as the beginning at Rockwell of what became the HELLFIRE program.

CASM

At the same time that Hornet was revived, a second program for testing laser seekers on air-to-ground missiles was under way at Elgin AFB in 1970, called CASM. Maverick missiles taken out of the production line were modified and equipped with Martin-Marietta designed laser seekers, as a precursor to the development of the tri-service seeker. This testing continued until 1973, the year HELLFIRE was formally offered for tri-service use.

F
JOINT STARS
GROUND STATION



Joint Stand-off Target Attack Radar System Ground Station (Joint STARS)

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Joint Stand-off Target Attack Radar System Ground Station (Joint STARS)

Project PEEK and the Mohawk SLAR System in the 1960's

An important problem facing ground commanders during the 1960's was that much of the information regarding strength and location of enemy ground forces was unreliable due to the limits of surface and airborne surveillance. Poor visibility due to weather or darkness and the inability to detect and locate moving vehicles over large areas were important limitations. Enemy forces could exploit these weaknesses by moving forces at night or in bad weather, or by moving forces so rapidly that surveillance lagged. It was clear that a system was needed to overcome these surveillance weaknesses. What was needed was an airborne system that would give ground commanders access to simultaneous, real-time information regarding enemy movements regardless of weather or darkness. Furthermore, the need existed for such an airborne sensor to provide information to help differentiate the locations of enemy versus friendly forces over a wide area.

In response to this problem, in the early 1960's the Army contacted with General Dynamics on an experimental radar known as Project PEEK or the Periodically Elevated Electronic Kibitzer. The basic concept underlying Project PEEK was that motion is the Achilles Heel of the modern ground army. This was based on the assumption that motion could be detected by an airborne moving target indicator (MTI) radar. However, because of the many technical and practical problems encountered the program was eventually cancelled.

Subsequent to the cancellation of Project PEEK, Chal Sherwin of the University of Illinois' Control Systems Laboratory continued working on MTI radar. Through subsequent Army funding the laboratory developed a prototype X-band moving target indicator (MTI) Side-Looking Airborne Radar (SLAR). The SLAR had a narrow, side looking radar beam that would trace a strip-map of the terrain and moving ground vehicles as the aircraft flew. Following this development the Army selected Grumman to develop the system consisting of the OV-1 or Mohawk aircraft. Motorola received the contract to develop the AN/APS-94 SLAR radar, a scope display and film processor to produce the strip map, and a data link to relay the information to a ground station. This early Mohawk SLAR system had limited capabilities but was deployed in Europe for surveillance across the Czechoslovakian and East German borders. It was also deployed in Vietnam to identify enemy vehicles moving along roads into North Vietnam from a stand-off distance.

Air Force Development Programs in the 1970's: MLRS3, MASR and Pave Mover

During the mid 1970's the Air Force began developing similar surveillance capabilities based on moving target indicator radar technologies. The Multi-Lateration Radar Surveillance and Strike System (MLRS3) technology demonstration utilized precision range measurements from two airborne L-band MTI radars to locate ground and airborne targets and to provide guidance to attack those targets. Because of the lack of technological maturity this program did not transition to engineering development.

However, the concept did lead to the MIT Lincoln Lab development of a GMTI radar for a fixed wing aircraft. This was called the Multiple Antenna Surveillance Radar (MASR). The principle advance of this program was the development of a precision, low sidelobe, electronically scanned displaced phase center antenna to provide the necessary degree of ground clutter reduction. The program also made important advances in programmable signal processors and surface acoustic wave devices.

Based on the developments of the MRLS3, and more importantly, the Army MTI developments, the Assault Breaker concept was proposed by the Defense Science Board in 1976. This concept for attacking Soviet second and third echelon armored forces was based on the use of a GMTI radar in a high altitude aircraft. In 1978 a joint Air Force/DARPA program called Pave Mover was launched that was based on the Assault Breaker concept. This program would build upon the earlier developments and add a synthetic aperture radar (SAR) mode. Competing development contracts were awarded to Grumman/Norden and Hughes. By 1980, in addition to the GMTI modes, the Pave Mover radars had SAR spot modes and were capable of switching between wide area MTI (120°-200 km), smaller area MTI (10 x 10 km), precision moving target track, and weapons guidance modes.

The Army Stand-Off Target Acquisition System (SOTAS)

During the 1970's, prior to, and in parallel with the Air Force MLRS3, MASR and Pave Mover programs, the Army initiated the Stand-Off Target Acquisition System (SOTAS) program (originally named ALARM). Initial program studies began in 1970 and built upon the developments of the Mohawk SLAR program. The program faltered in its initial years with two cancellations between 1970 and 1973. However, in 1973 when Norm Augustine became Assistant Secretary of the Army for R&D, strong support followed as a result of his strong belief in the potential of this system. Support for the program was also enhanced as a result of analyses on military tactics used in the 1973 Israeli-Egyptian war that suggested that a system with SOTAS capabilities could be extremely useful. This resulted in an increase in TRADOC support. That same year a very talented engineer, Bill Kenneally was named SOTAS Program Manager of the ERADCOM (Electronics Research and Development Command) program office.

The SOTAS requirements included a moving target radar mounted on a Blackhawk UH-60A Sikorsky helicopter (later YEH-60B). The system also included an anti-jam data link for sending real-time transmissions to the ground station. The ground station was then capable of sending the information to a tactical operations center and ground commanders. The ground station consisted of a computer processing and display terminal installed in a shelter module on a five ton truck. The module included space for a two person crew. The radar was capable of operating at extended ranges so the helicopter could remain in friendly airspace. The new radar would provide immediate targeting and intelligence information on almost any moving ground target.

By May 1976 an experimental model of the system was sent to Korea for testing. The Korean test was followed by SOTAS testing as a part of the Reforger exercises in Germany in September 1976. Feedback was so positive that the decision was made to build two complete development systems known as Interim-Interim SOTAS (or I²SOTAS) for the US Army-Europe (USAEUR). The I²SOTAS were used in both the 1978 and 1979 Reforger exercises. These early tests demonstrated the efficacy of the

system and provided valuable feedback to the Army program office and the contractors. As a result of the successful demonstrations in the Reforger exercises full scale engineering development was approved by a Defense Systems Acquisition Review Council (DSARC) in August 1978.

Two companies submitted offers in response to the solicitation. These included General Dynamics, who had been the contractor for the advanced development models, and Motorola, who had developed the AN/APS-94. The original government baseline cost estimate was \$92 million. The General Dynamics proposal was \$103 million. The original Motorola proposal was for \$79 million, however, following negotiations and the request for best and final offers, Motorola submitted an amended proposal for \$55 million. This would create the seeds for serious problems later. The Motorola Government Electronics Division was awarded the contract for SOTAS full scale engineering development in July 1979.

Following the award of the contract problems started to develop almost immediately. Ed Soohoo, the Motorola proposal manager, who had been hired from Lockheed left almost immediately. He had performed extremely well on the proposal and the government program office assumed that he would continue as the Motorola program manager. Soohoo was replaced by Brian Fugit who resigned shortly thereafter, the same year. Subsequently Motorola named Irving Luke as program manager. This level of turnover among PM's was ostensibly dysfunctional.

A second major problem was based on the fact that Motorola was not validated for the Cost Schedule Control Systems Criteria (CSCSC), the government's accounting system for major programs. It took the company almost two years and \$2 million to become compliant. Schedule and cost problems began to develop early on in the program. By the end on 1979 the program had a \$12 million overrun. By the end of February 1980, the overrun was estimated at \$27.5 million with a six month schedule slip. To compound problems, on the \$11 million Motorola subcontract to Lockheed for the E-Scan antenna, Motorola had insisted on very tight specifications, although the prime contract allowed for trade-offs in meeting performance requirements. Motorola was not inclined to be flexible on the specifications and within nine months the subcontract had grown to \$40 million. Bill Kenneally, the government deputy program manager observed that Motorola was following a commercial pattern of managing Lockheed like a components vendor rather than allowing them the appropriate level of flexibility with the specifications.

While technical performance on the part of Motorola was quite good, by the spring of 1981 the cost overrun and schedule delays prompted Richard DeLauer, the Under Secretary of Defense, to initiate a DSARC review of the SOTAS program. As part of the review the Defense Science Board recommended the continuation of SOTAS. During the review the program manager, Colonel Crawford was asked to summarize the program's current status. He indicated that costs were finally under control and that all of the major technical problems had been resolved. He was asked if Motorola would accept a fixed price cap on the contract. Colonel Crawford answered affirmatively.

Subsequently negotiations were initiated with Motorola to alter the contract. Motorola indicated that they would agree if certain specifications would be modified. No agreement could be reached and Motorola declined to accept a fixed price cap. As a consequence, General Paige recommended termination with the concurrence of Dr.

DeLauer. However, it is important to note that General Paige's support for termination was based upon a high level of confidence that the program would be resurrected by Congress for Fiscal Year 1983. He had worked with Tony Battista, the senior staff member on the House Armed Services Committee, who had supported the termination action and had agreed to sponsor a new Army SOTAS program in the next budget. Hence, in December 1981 SOTAS was cancelled. Ironically, General Paige did not know that discussions were beginning to develop for a radical change in the entire SOTAS concept. This would be a joint Army-USAF program merging the previous Army SOTAS and Air Force Pave Mover programs. This would be known as the Joint Stand-off Target Attack Radar System (Joint STARS).

Joint STARS: The Merging of the SOTAS and Pave Mover Programs

By 1982, it was apparent to both the House Armed Services Committee and the Office of the Secretary of Defense that two separate programs (Army and USAF) with significant overlapping requirements would not be cost effective. With the cancellation of SOTAS in May 1982 the Joint STARS program office was established at the Electronic Systems Division at Hanscom AFB, Massachusetts. The mission would be to develop a single multi-mode target acquisition and attack system. Initially, the Army was a reluctant partner but had no other alternative to the joint program to meet their GMTI requirement. So discussions were initiated that would determine the division of labor between the Army and the Air Force. Early on it was determined that the Air Force would assume responsibility for the platform (aircraft). Developments from the Pave Mover program and the work of Grumman and Hughes demonstrated how a common radar could be developed to meet the Air Force requirement for a synthetic aperture radar (SAR) and the Army requirement for a moving target indicator (GMTI). Because of the advances that had been made by the Army on the SOTAS ground station it was determined that the Army would assume full responsibility for the ground station program including the data link.

In 1982, the Army created the Joint STARS Ground Station Module project office at ERADCOM. Because of his experience with SOTAS, Bill Kenneally assumed the position of Deputy Project Manager in overseeing design studies and the development of systems specifications. Because of the complexity of the system, and the complication of the interface with the Air Force, the determination of requirements took longer than expected. Reaching agreements were prolonged and changes were numerous in 1982 and 1983. A number of decisions required compromises and trade-offs and this tended to prolong the decision process. For example, ideally SAR would utilize a small antenna on a fast moving aircraft. However, GMTI required a very large antenna and a slower moving aircraft. These types of trade-off decisions resulted in significant delays.

At one point one option under active consideration was a two-phased program in which the radar would be initially deployed on ten conventional aircraft, with subsequent production focused on a stealth platform derived from the Tacit Blue test aircraft. Tacit Blue was to be a low observable surveillance aircraft that would carry the Joint STARS GMTI/SAR radar with low probability of intercept features. The aircraft was successfully flown in 1982 and accumulated 135 test flights. However, the inherent impossibility of making the radar undetectable was finally realized. This issue, coupled with the high cost of the plane, led to the dropping of this option. The Army naturally favored its OV-1 twin

turboprop Mohawk aircraft, but the Air Force would exercise the greatest influence over the platform decision. The TR-1, a derivative of the U-2, was also seriously considered as the platform. However, the limitations of this aircraft resulted in its rejection. The B-52 and the C-130 were also considered, but in May 1984 a Joint Initiatives Memorandum from the Air Force and Army chiefs of staff decided the matter by selecting a militarized Boeing 707 that would be known as the E-8A.

During the same timeframe it was determined that because of its technological maturity, the design characteristics of the preceding SOTAS ground station would be adopted for the Joint STARS Ground Station Module. This decision would result in significant cost savings and schedule reduction. Thus, in August 1984 Motorola was awarded the full-scale engineering development contract for the Ground Station Module. The contract included the development and production of six GSM's with an option for two more. Immediately following the contract award the Joint STARS GSM project office obtained a pre-full scale development GSM (i.e., a modified SOTAS ground station) for field evaluation. The capability to interface with the Tactical Fire Direction System (TACFIRE) had already been verified. Tests were conducted on the interface with the maneuver control system tactical computer terminal.

The Joint STARS GSM project office tasked Motorola to develop and integrate a capability for the GSM to display data from an APS-94F radar and the UPD-7 data link. During November 1984 the capability to use APS-94F/UPD-7 data was incorporated into the GSM. Next, in January 1985, the pre-full scale development GSM was utilized during the Reforger exercises in Europe. The GSM demonstrated its interoperability with deployed units including TACFIRE and the APS-94F/UPD-7 radar and data link. During this same year the Army Joint STARS GSM project office transitioned from ERADCOM (this later became Army Research Laboratories) to Fort Monmouth with the Communications and Electronics Command (CECOM). At Fort Monmouth the project office would also be supported intensively by the Electronic Warfare Reconnaissance, Surveillance, and Target Acquisition Directorate (EW/RSTA).

While progress was occurring on the Ground Station Module, requirements decisions and changes prolonged the proposal schedules and contract award date on the other major components of the system. In fact, Norden engineers complained that they were required to rewrite their proposal following yet another round of requirements changes. Finally, following a Source Selection Evaluation Board review of proposals, in July 1985 Grumman Corporation (now Northrop Grumman) was selected as prime contractor for full scale development. Their primary responsibilities included systems integration, signal processing, and the aircraft conversion. The total contract for \$657 million included two development systems and support for developmental testing. Norden Systems was selected as the subcontractor for the SAR and GMTI radar. Harris Corporation was selected to be the subcontractor to Motorola on the communications data links. Other major subcontractors included Mitre for technical monitoring and systems integration, Telephonics for some of the on-board electronics, Rolm Mil-Spec Computer Company for the computer disk storage, Control Data Corporation for programmable signal processors, and Magnavox for the UHF communications system.

The Joint STARS System Characteristics and Capabilities

The capabilities of the Joint STARS system would include the ability to locate and track moving ground vehicles, including the discrimination of tracked from non-tracked vehicles. The system would operate day or night and in most weather conditions. The SAR and GMTI radar would be capable of operating in an electronic counter measures environment (ECM). The Boeing 707 (E8A) aircraft would have the capability of refueling in mid-air and could remain in its orbiting pattern for up to 20 hours.

The system would be capable of conducting ground surveillance to develop an understanding of the enemy's location and to support attack operations and targeting that would contribute to the delay, disruption and destruction of enemy forces. While flying in friendly airspace the system would be able to look deep behind enemy lines to detect and track ground movements in both forward and rear areas. The system would have a range of 250 kilometers with the 120 degree field of view covering nearly 50,000 square kilometers. These capabilities would be useful not only during actual combat, but in assessing impending military aggression, international treaty verification, and border violation.

The radar data would be transmitted via the secure data link to the Ground Station Modules. The GSM's would be deployed to Echelons Above Corps, Corps, Corps Artillery, Division, and Division Artillery levels. This capability to disseminate near real-time intelligence about moving and fixed targets would provide a critical advantage to Army forces. The radar would have the capability of performing sector searches inside a wide area field of view in either high or medium resolution search modes, providing both synthetic aperture radar, fixed target indication imagery and smaller area GMTI display. By focusing on smaller terrain areas the radar image would be enhanced for increasing resolution display. This high resolution would be used to define moving targets and combine combat units with accurate information for attack planning. The radar would revisit an area of interest at frequent intervals. During this time, the default mode of the radar would be wide area surveillance, revisiting the entire coverage area periodically unless tasked otherwise by the operators. Within this timeline, the system would be capable of providing wide area situational awareness, while allowing operators located in the GSM's to send requests to the Army operators on the E8A aircraft. In addition, it would be possible to simultaneously scan a number of smaller areas inside the primary area of interest. A diagram of the GSM is presented in Figure 1 on the next page.

The E8A aircraft would be staffed with Air Force and Army operators and the GSM's would be staffed with Army personnel. The aircraft would have 10 operations consoles and two communications consoles. This would be increased later with the E8C. The aircraft would also be equipped with a 24 foot phased-array radar antenna housed in a 40 foot canoe shaped radome located under the forward part of the fuselage. The radar equipment would be housed in the forward bottom cargo bay directly above the radome. In addition to communications antennas, the E8 aircraft would have two data link antennas to provide a continual data link to the GSM's. A diagram of the interior of the E8A is presented in Figure 2.

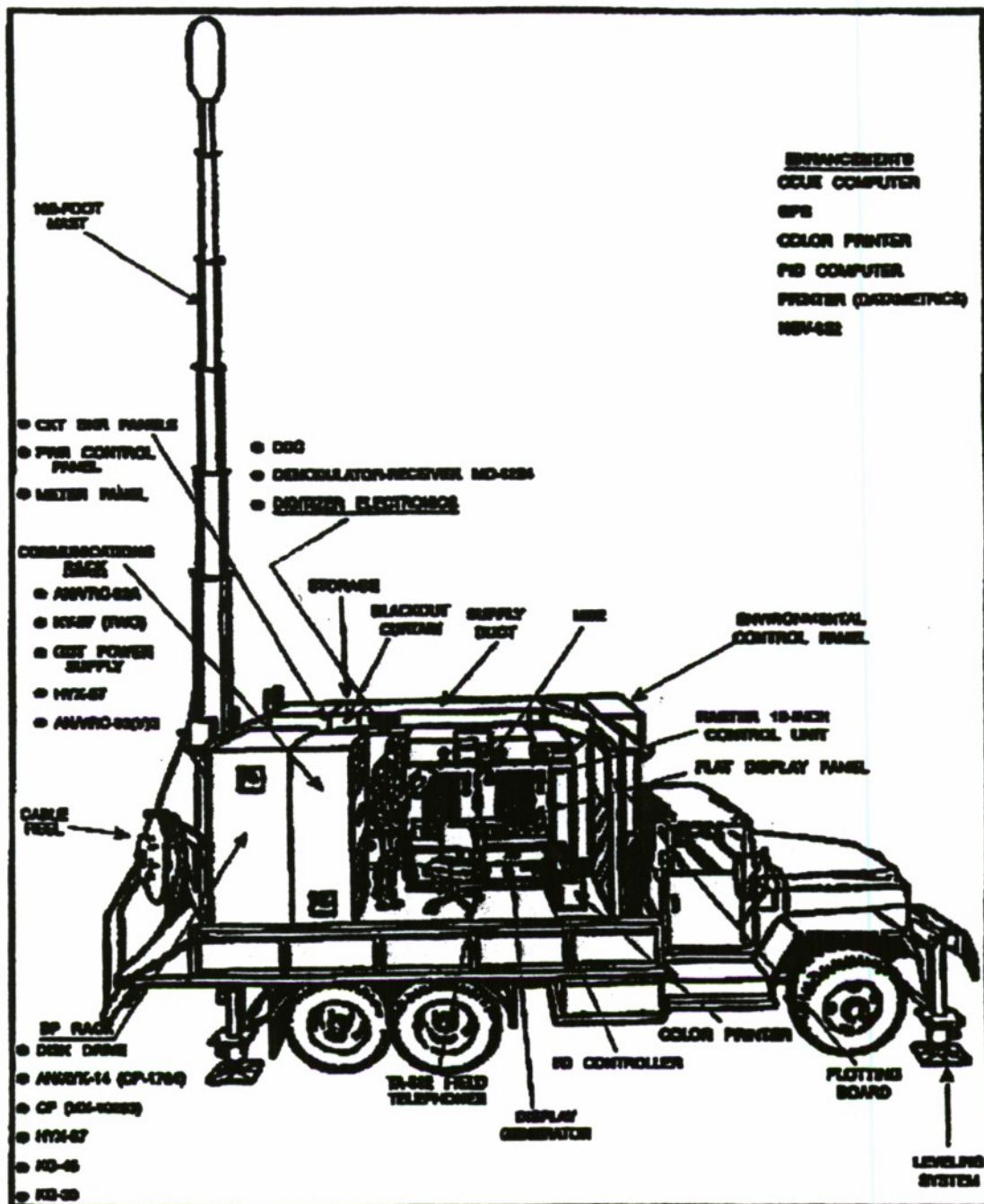


Figure 1 – Interim Ground Station Module (GSM)

The Synthetic Aperture Radar/Fixed Target Indicator (SAR/FTI) data transmitted to the GSM's would produce a photographic negative-like image or map of selected geographic regions on the GSM display monitors. SAR maps would contain precise

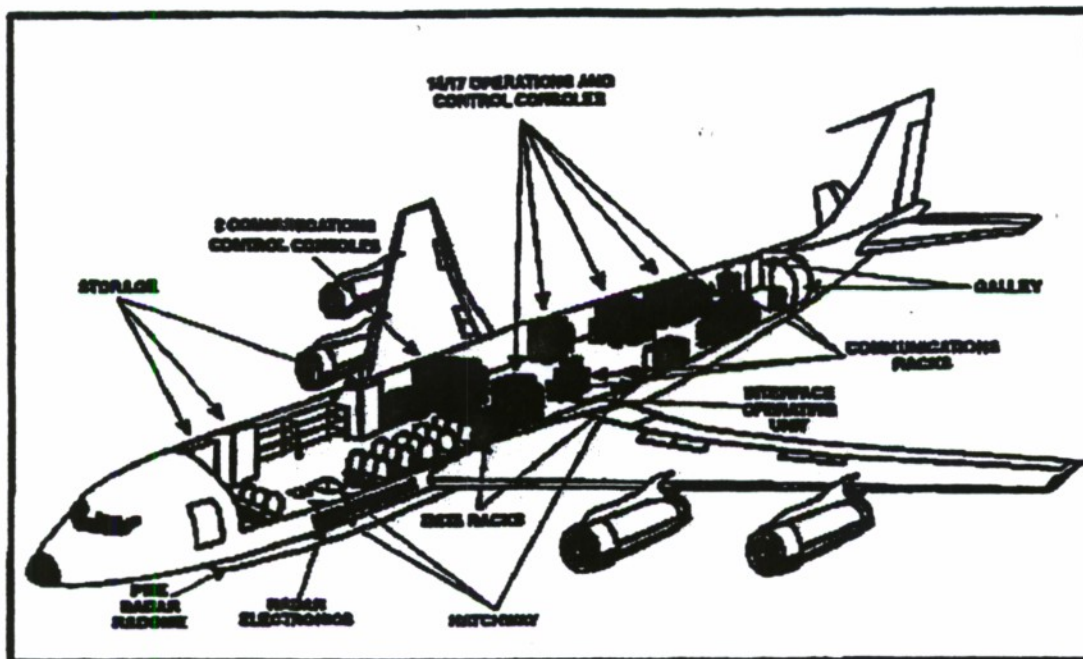


Figure 2 – E8A aircraft interior

locations of critical non-moving targets such as bridges, harbors, airports, buildings, or non-moving vehicles. The E8/GSM data link would be a wide band, anti-jam, two way data link known as the Surveillance Control Data Link (SCDL). The E8 and the GSM's would also be linked through secure UHF and VHF radios. The GSM's would be equipped with standard tactical communications, and secure commercial communications. In addition to receiving the Joint STARS radar data the GSM's would interface with the Army weapons systems and communicate radar coverage requests back to the Army operators on the E8 in the air.

The GSM would include the capability of storing data and graphics in data storage cartridges. Copies of messages could be printed on a line printer, and a three color screen printer would produce a color hard copy of the console screen. The GSM system would include two 30 kW 50 to 60 Hz generator power units. The generators would be towed by the two M-923 five ton cargo trucks. One truck would be unmodified and would be used as a support truck to carry spare equipment and other essential items. The second truck would be modified with a mechanical leveling system and would carry the GSM S-679 shelter. The GSM shelter would include an environmental control unit, a retractable 100-foot pneumatic mast and cable reel system. The mast would include the SCDL and UHF antenna. The two operator consoles would include a scan screen, two menu driven display monitors, and a militarized keyboard. The consoles would receive data from the ground data terminal (GDT). The GDT would consist of a digital-to-digital

converter, a 400Hz converter, a lower control unit, a Joint STARS interface unit, and the SCDL graphics would be digitized from maps onto screens via a digitizer, small and large plotting boards, and a map "bug." (A map bug is an electronic device that allows operators to trace map data and graphics, and transfer information to the computer, which enables maps and graphics to be displayed on the operator's monitor.) Data and graphics would be stored on removable disks.

Controlling Schedule and Costs: The Major Challenge for the Motorola and Government Project Managers

Through 1985 and 1986 work on the GSM at the Motorola government electronics division facility in Scottsdale, Arizona progressed. Under the leadership of program manager, Irving Luke, the schedule and cost performance was improved significantly when compared to the SOTAS program. Luke and other Motorola managers had learned from the SOTAS experience and this, coupled with the relative technological maturity of the GSM, facilitated schedule and cost control. However, through 1985 and 1986 significant challenges to schedule and cost control began to emerge. The challenges were largely the result of requirements changes. For example, at the start of the Joint STARS GSM program the Army determined that the aging ground processing facility for the OV-1D Mohawk airborne radar system could be replaced with the new Joint STARS GSM with minor modifications. By 1985 the Army approved a plan to acquire nine development GSM's beginning in 1987 as "limited production urgent" units for use with the Mohawk radar system. These units would initially have less capability than the production GSM's for Joint STARS that would be scheduled to enter full-rate production in 1989. The plan would allow for retrofitting later to provide full capability. This requirement change in 1985, however, resulted in a \$7 million increase for incorporating the capability to process radar data from the OV-1D Mohawk UPD-7 radar system.

Another requirement change resulted from the rapidly evolving display technology. During this timeframe the rate of improvement in display resolution was such that the Army project office instituted the requirement change to improve the display to receive the high resolution imagery from the radar system. This resulted in a cost increase of approximately \$25 million.

Bill Gebele of the government project office noted that another major requirement change in 1986 was the result of the TRADOC decision to create two models of the GSM. This change was a result of the Army Vice Chief of Staff's directive to move toward a lighter more mobile force. The first model would be the Medium GSM. This was the version currently under development that would be carried on a five ton truck. The second GSM version would be the Light GSM. This version would be outfitted on high mobility multi-purpose wheeled vehicles (HMMWV). The \$40 million contract was awarded to Motorola in 1986 for the development of the Light GSM. The plan called for 70 Medium GSM's and 25 Light GSM's to be produced and fielded by 1994. While this new requirement resulted in a contract to Motorola, the result was another source of pressure on the schedule for the engineering development program.

The computer technology and software were evolving rapidly during this timeframe. Motorola continued to improve the time compression software that recorded GMTI radar data over a period of time to track the target start point and route. The time integration software also continued to be upgraded. This allowed for the system to

overlay successive frames on top of each other over a selected period and display them at one time on the screen. The time integration software would allow for the rapid identification of main supply routes, assembly areas, and logistics sites. These methods required every dot reported on the radar to have an associated time tag and Universal Transfer Mercator (UTM) code. By cross-cuing with SAR data, target locations could be confirmed. The software development also included a capability to estimate time of target arrival to selected points or along projected routes. These tasks represented significant software challenges. While significant progress was being made, by 1987 a major software flaw was identified. The problem amounted to the inability for the two workstations on the GSM to handle simultaneous tasks. This resulted in additional schedule delays and cost increases.

To compound the budgetary situation further, in 1987 Congress appropriated less for the Joint STARS GSM than what the Army had determined to be necessary. That same year the authorization was reduced from what was originally appropriated. At the same time the Army diverted some of the funds to another critical program. In total, by the end of 1987 the cost of the GSM development program had grown by \$72 million. The schedule for the GSM developmental/operational testing had slipped from second quarter FY 1987 to fourth quarter FY 1988. The schedule for full rate production slipped to FY 1989. By the end of 1988, Al Pavik was named Motorola Joint STARS GSM program manager, replacing Irving Luke.

As the engineering development phase progressed on the GSM, by August 1987 Grumman delivered the first developmental E8A for testing. Due to delays in radar development, the first test flights took place without the radar. In April 1988, the Defense Acquisition Board instituted a major program change. It increased the number of E8 aircraft to be built to 22 from the 10 originally planned. The board also approved a program plan to use new Boeing 707 aircraft (the militarized versions were designated the E8B) instead of the used platforms that were acquired for the E8A. The first two E8A development aircraft were 20 year old commercial Boeing 707 planes that had been acquired from American Airlines and Qantas. Upon the acquisition of these aircraft, Grumman first performed the conversion at their Lake Charles, Louisiana facility and subsequently sent the aircraft to their Battle Management Systems Division in Melbourne, Florida where the electronics systems were installed and tested. Their ostensible conversion difficulties and questions of remaining service life convinced the board to have subsequent aircraft be new 707 E8B airframes.

By April 1988 the first tests without the radar had been completed. Subsequently the Norden radar systems were installed. The second developmental E8A was delivered in November 1988, complete with radar. In December 1988 the first full flight tests were conducted with the radar. By August 1989 the GSM's were ready for the first tests that would include the entire Joint STARS system.

The plan to purchase new Boeing 707's for the production Joint STARS systems was derailed in October 1989 when Boeing announced that it would discontinue production of the airframe upon the completion of a final order of British and French airborne warning and control system (AWACS) aircraft. In November 1989, the Pentagon approved the re-baseline of the program to use older 707 airframes in what would be labeled the E8C configuration. The program office had examined other options, including the Boeing 757 and 767, and the McDonnell Douglas MD-11. However, these

options were considered cost prohibitive and the change in configuration would have jeopardized the program schedule.

By 1990 the DOD Joint Requirements Oversight Council program plan called for the production of 20 E8C aircraft through 2002 (from used 707's) and the production of 100 GSM's. By 1989 nine development GSM's had been produced. These were labeled as Limited Procurement Urgent (LPU) because these GSM's did not have the full capability of the Joint STARS GSM's. They were deployed as replacements for the obsolete AN/UPN-7 ground station for the Mohawk Side-Looking Airborne Radar. The first version of the GSM to actually be used with Joint STARS was labeled the Interim Ground Station Module (generally notated GSM). Eight engineering development Interim GSM's were completed for testing by 1990.

By 1990 Motorola and the Joint STARS GSM project office were well under way on the development of the Medium GSM and the Light GSM that would replace the Interim GSM for the actual production Joint STARS systems. The Medium GSM would include enhancements such as a downsized electronics suite, an enhanced man/machine interface with extensive Built In Test Equipment capabilities. The system would also include the ability to simultaneously display and analyze data from multiple sensors. The Light GSM was also beginning development. The Light GSM would be mounted on a High Mobility Multipurpose Wheeled Vehicle. This would provide light forces with a C130 Joint STARS capability. The system would have the capability of operating on the move.

The turning point for the Joint STARS program came in August 1990 when Iraqi forces invaded Kuwait. Although the production systems were not scheduled to be deployed until 1997, in September, 1990 the two prototype Joint STARS systems were sent to Europe to participate in Operation Deep Strike as an operational test. The Deep Strike exercises simulated a large "Soviet" ground force attack against NATO forces. At one critical point in the exercises, Lt. General Frederick Franks, the Army VII Corps commander, used the data disseminated from the Joint STARS ground station to identify and counterattack a "Soviet" armor column, played by a Canadian tank convoy. The engagement resulted in simulated destruction of over 50 tanks. General Franks and General John Galvin, Supreme Allied Commander, Europe became immediate converts and briefed General Schwarzkopf on the results. By early December, following a Defense Science Board recommendation to deploy, a Joint STARS team traveled to Riyadh to discuss the feasibility of deploying the pre-production, development systems with Gen. Schwarzkopf's staff. On December 17 the order came to move the prototype Joint STARS systems to Saudi Arabia for immediate service.

Performance in the Gulf War

Following the decision to deploy the two prototype E8A aircraft and six Joint STARS GSM's to the Persian Gulf, on December 17, 1990 Motorola and Grumman were notified. Preparations began immediately for the first Joint STARS deployment. Because the system was still in engineering development, crews consisted of a mix of contractor and military personnel. In addition, Motorola sent a contingent of software engineering staff for support of the six GSM's. During the end of December and early January, Motorola software engineers worked feverishly to make final adjustments for

data dissemination from the six GSM's and obtain satellite capabilities. Similar efforts were made by Grumman personnel on the aircraft.

On January 12, 1991, the Joint STARS team under the command of Col. George Muellner arrived in Riyadh, Saudi Arabia. Two days later on January 14 the system began conducting operational missions. This was 48 hours prior to the start of the air war. The aircraft flew in Saudi airspace by night and were protected by fighter combat air patrols.

The Gulf War resulted in a modification of the plan of operations for the system. Planning had called for a radar management officer on the E8 to be an on-board conductor, parceling out Army GSM requests for the various types of radar views. However, in the Gulf War, prior to the ground war, Joint STARS would assume a critical role in directing air power against Iraqi ground targets. This turned out to be devastatingly effective in its consequences against the Iraqi ground forces.

Each night the Joint STARS aircraft would take off from the central Saudi Arabian air base initially viewing large specific areas of the Kuwaiti theater of operations, using the radar in wide-area surveillance mode. The crew would then execute a list of targeting priorities, looking intensely at smaller areas with both the moving target mode and the stationary target synthetic aperture radar mode. Then, in real time, the crews would process cues from other intelligence sources to find specific targets. The radar data would be transmitted to the six GSM's. One GSM was located at USAF Central Command Headquarters in Riyadh. Marine Headquarters had one GSM. Central Command-Army had two GSM's, with one for the rear echelon and one to send forward. The Army VII Corps had a GSM, as did the Army's 18th Airborne Corps.

Throughout the war Joint STARS provided timely and reliable enemy ground order of battle and targeting information to Coalition commanders. The tactical targeting intelligence from Joint STARS was responsible for three major strategic decisions during the war. The system played a major role in tracking SCUD missile mobile launchers by night. The system operated every night of the war, including 49 combat sorties and over 535 hours between the two Joint STARS aircraft.

On one critical mission the system detected an Iraqi vehicle column moving toward Khafji. Joint STARS vectored two A-10's and an AC-130 gunship to the convoy. This resulted in the destruction of 58 of the 71 vehicles. In another critical mission General Schwarzkopf used the system to verify that the Iraqi's were not reacting unfavorably to his deception plan as he built up his forces to the west in preparation for the massive flanking attack of Coalition ground forces. Twenty four hours prior to the ground attack Joint STARS detected a significant Iraqi force movement in the west. The column was immediately attacked with numerous ATACMS missiles followed by fighter bombers. This resulted in the nullification of the Iraqi attempt to counter the Coalition attack in the west.

In perhaps the most crucial role played by Joint STARS, the system tracked the Iraqi retreat from Kuwait City. The GMTI radar imagery is presented in Figure 3 on the next page. Joint STARS provided real-time information on the retreat. This information allowed commanders to use tactical air power to interdict and destroy the Iraqi mechanized columns as they moved out of Kuwait City. The operation was such an overwhelming defeat for the Iraqis that then Defense Secretary Cheney described it as

"The Mother of All Retreats" (in satirical response to Saddam Hussein's reference to the anticipated "Mother of All Battles").

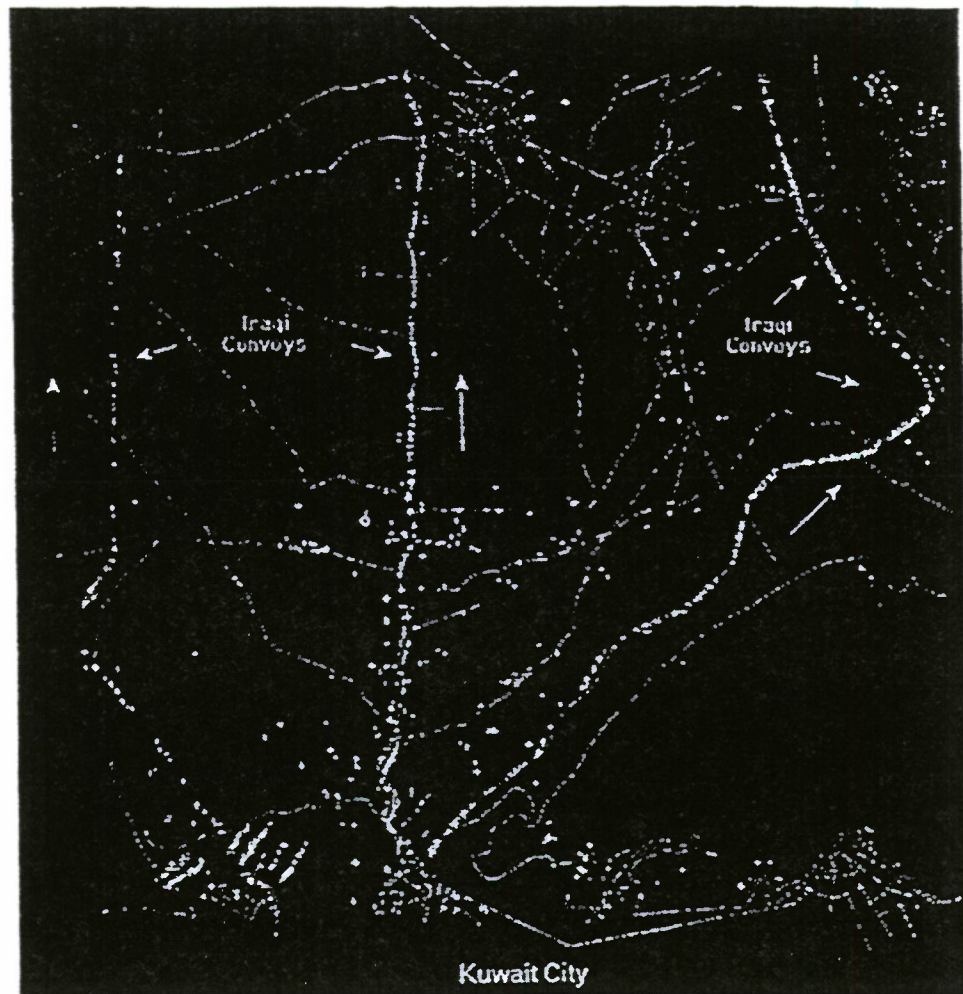


Figure 3 – GMTI radar imagery of Iraqi retreat from Kuwait

Lesson 1: Early Deployment in a Crisis can be an Important Operational Test

The decision to deploy the engineering development Joint STARS GSM's and E8A's in the Gulf War almost six years prior to initial operational capability was a bold decision. This decision was clearly a calculated risk. However, the conservative decision to not deploy would have resulted in the loss of an opportunity for an important operational test. It would have also resulted in the loss of an opportunity to prove the system's capabilities and gain valuable support for the program's future funding.

A great deal was learned from the Gulf War experience. GSM dissemination of information to Army commanders had been slower than required. In addition, with 16 radios operating simultaneously during full utilization, there were delays due to frequency management. This vital experience resulted in subsequent improvements in the

utilization of GSM transmitted data. The critical need for more consoles for both Air Force and Army personnel on the E8 was also found during the Gulf War experience. Retired Mitre executive, Charles Fowler, observed that most of the early radars deployed during World War II were developmental. Incremental improvements were made as a result of operational experience. He noted that the potential value of testing the prototype system under conditions of combat should not be underestimated.

Lesson 2: The Gulf War Performance of the GSM's was Made Possible by the Level of Technological Readiness Achieved by the Start of the Joint STARS Program

It is likely that the GSM's would have never been ready for deployment in the Gulf War if a high level of technological readiness had not been achieved by the start of the Joint STARS program in 1984. For example, Bill Gebele of the government Joint STARS GSM project office observed, by the time the SOTAS program was cancelled the data link was completely developed. With the launching of the Joint STARS GSM program the data link simply required incremental preplanned improvements. Allan Tarbell of the GSM project office observed that the time compression and time integration software that was pioneered during the SOTAS program was a central technology in the GSM. This work was largely accomplished in the 1970's and then incrementally improved with the software upgrades in the 1980's. This capability was central to the GSM's operational effectiveness in the Gulf War.

Allan Tarbell also noted that a major technological advance that had emerged from the commercial sector in the 1980's was the transition from stroker displays to raster scanning color monitors. This allowed for significantly greater resolution in the display of the radar data. The relative maturity of this technology allowed for a smooth transfer to the GSM display monitors. This had important implications for the interpretability of the data. Finally, the rate of advance in data processing speed was a major contributor the GSM's capability by the time of the Gulf War. The maturity of this technology could also be attributed to commercial advances in computing.

Lesson 3: A High Level of Cooperation from the CECOM Labs Contributed to Technological Readiness

The government laboratories played a major role in the development of the GSM. Dating back to the SOTAS program, ECOM and then ERADCOM provided a high level of support for the program. With the creation of the Program Executive Office (PEO) structure and the launching of the Joint STARS GSM project in the early 1980's, CECOM assumed a central role in supporting the program. Throughout the early development there was movement of ECOM, ERADCOM, and then CECOM engineers into the project office as the program evolved. In fact, almost all of the early members of the project office came directly out of the laboratories. In addition, during the early years collocation of engineering personnel was used to facilitate the solution of a wide range of technical problems. While a number of the important technologies incorporated in the GSM came from commercial sector, and some came from the contractors (e.g., time compression and time integration), the CECOM laboratories were involved in several critical areas. These included antenna design, materials decisions such as the use of carbon graphite in the antenna, signal processors, transmitters, simulation, testing, and other supporting tasks.

Lesson 4: Underestimating the Learning Curve

When Motorola was awarded the SOTAS contract in 1979 both the company and the government project office underestimated the learning curve for Motorola. This learning curve, however, had little to do with the technologies themselves. Both Allan Tarbell and Bill Kenneally indicated that Motorola had excellent technical depth in all the relevant technical areas. The company had extensive experience with most of the key technologies involved in the system. In addition, while Motorola was primarily a commercial firm, there were definite synergies with the program requirements in terms of technical core competencies. Thus, the difficulties were not related to integrating technology. Rather, the learning curve was more programmatic in nature.

Motorola had been a first rate component supplier. However, the leap to becoming a systems integrator in a business in which it had limited experience (major defense systems) would prove to be more problematic than either the company or the government had anticipated. As discussed earlier, by the start of the SOTAS contract the company had not been validated for the CSCSC, the government's accounting system for major defense programs. Bill Kenneally and Allan Tarbell observed that while Motorola possessed the necessary technical capabilities, program management was not adept at managing defense projects and the cost overruns soon spiraled out of control. As noted previously, a major contributor to the cost overruns was the inaccurate cost estimating at the beginning that allowed for the bid that was \$37 million below the government's own estimates. Finally, the failure to negotiate a reasonable price cap with the government for SOTAS engineering development led to the cancellation of the contract. Charles Fowler hypothesized that with greater managerial experience in the defense business, this event may have been avoided. To Motorola's credit, during the early years of the Joint STARS GSM program the government electronics division was able to gradually make the necessary adjustments and improvements in program management.

Lesson 5: Field Demonstrations to Gain TRADOC Support and Funding Stability

An important element of the Army's air-land battle doctrine is the ability to command and control a fast moving, complex battlefield and to strike deep into enemy territory. This required the surveillance capability to look far behind enemy lines to accurately detect enemy forces and to bring weapons to bear against them. The requirement for this capability, however, did not necessarily mean that one particular approach would be adopted without the challenge of obtaining and maintaining TRADOC support.

While theoretically Joint STARS, and SOTAS before it, could vastly increase the Army's surveillance capability, the program needed to demonstrate the potential of the system to ensure necessary support. Beginning with SOTAS, and continuing through Joint STARS, the approach of using field demonstrations served two purposes. It allowed for useful testing, but also helped to build wide support for the program.

Hence, early in the SOTAS program experimental systems were assembled from largely commercially available components and taken to Fort Ord Combat Development Experimental Command for technology demonstration. With the development of the system, by 1976 the prototype system was being demonstrated in the Reforger exercises

in Germany. The success in the Reforger exercises resulted in further support for the program and essentially guaranteed funding stability through 1981.

In 1990 the use of the two prototype Joint STARS systems in the Deep Strike exercises in Europe convinced General Franks and General Galvin that the system should be deployed in the Persian Gulf. Charles Fowler hypothesized that if the decision had been made to not send the system to the Gulf, subsequent funding in the 1990's may have been jeopardized. In contrast, the spectacular success of Joint STARS in the Gulf War virtually insured funding stability for most of the decade of the 1990's.

Lesson 6: Requirements Instability and Non-Essential Requirements have an Adverse Impact on Schedule

While the GSM program experienced relative funding stability, it suffered from a degree of requirements instability. Beginning with SOTAS, at the defense acquisition board review, a request was made that the system have an electronic scanning capability in addition to the mechanical scanning ability that had already been designed. Lt. General Cianciolo, the first SOTAS program manager indicated that this requirement was not challenged in order to facilitate DoD approval. However, in retrospect, this turned out to be a mistake. The requirement was not actually essential, and neither Cianciolo, nor anyone in the government project office at the time could have predicted that this requirement would become the major cost overrun and schedule problem in the SOTAS program.

Following the SOTAS cancellation, during the 1982-84 proposal timeframe, there was significant difficulty in reaching consensus on requirements. As noted previously, this resulted in a number of changes that prolonged the contract award schedule. This problem was even more profound on the Air Force side, resulting in significant delays.

As work progressed on the GSM (later labeled the Interim Ground Station Module or IGSM), in 1985 the decision was made to produce nine "limited production urgent" units for the OV-1D Mohawk airborne radar system. Next, in 1985 the display monitor requirements were changed in response to the rapidly evolving technology. These changes resulted in further software modifications.

In 1986, in response to directives from the Army Vice Chief of Staff, the decision was made to design two versions of the GSM. As noted previously, these would include a Light GSM and a Medium GSM, known as the Block I Series. With this requirements change, the Interim Ground Station Module would never go into production and engineering development work would progress on the Light and Medium GSM's. This, of course, had subsequent schedule implications.

In addition to requirements changes, the issue of non-critical requirements in terms of extraordinary nuclear, chemical, and biological survivability specifications contributed to further schedule delays. Charles Fowler observed that the inflexibility of the procurement system that enforced a uniform, standardized acquisition process was also a major contributor to the schedule problem. The problem stemmed from the fact that the acquisition system essentially managed the acquisition of small scale customized systems in a similar manner to systems with large scale production runs. Fowler suggested that the acquisition system should be modified or streamlined for systems with small production quantities. A very visible and successful example of this would be the Guardrail program.

The problem of requirements changes creates a significant challenge for any program manager. This was no exception for Bill Kenneally and Bill Gebele of the Joint STARS GSM project office, and Irving Luke and Al Pavik of Motorola. The usual approach is to freeze the design at some optimal point, develop prototypes, move into testing and production, and then through a subsequent program of preplanned product improvements to incrementally upgrade the system. In the case of the Joint STARS GSM this logic would have suggested freezing the design of the Interim GSM (IGSM), and following testing, moving into production of the IGSM. Concurrent progress would occur on the Light and Medium GSM's that would follow. Both Allan Tarbell and Bill Gebele of the Joint STARS GSM project office concurred that this is what would have been expected. However, the IGSM never went into production (although the engineering development prototypes were deployed in the Gulf War). Work proceeded on the Light and Medium GSM's further prolonging the development schedule.

Lesson 7: Design Flexibility and Open Architecture for a Technology Insertion Program

From the start of the Joint STARS program through the Gulf War computer technology was advancing rapidly. As a consequence, changes in both hardware and software occurred as the program proceeded. During the 1980's the system utilized custom designed militarized versions of commercial computers. This resulted in significant cost and schedule implications for each successive generation of upgrades.

Following the Gulf War, in the early 1990's significant changes in the form of open architecture and increased use of commercial off-the-shelf technology resulted in reductions in cost and schedule for upgrading computer hardware and software. Similarly, Joint STARS was ahead of its time in developing programmable sensors. The use of open architecture, design flexibility, and the use of commercial off-the-shelf technology became a model for other systems. From the very beginning Motorola utilized commercial components and existing military equipment to the degree that the military specifications would allow. As the system evolved the use of commercially available components increased. In the 1990's this transformation accelerated with the sweeping changes in the acquisition system under Defense Secretary William Perry.

With reduction in military specifications and the emphasis on the use of commercial technology, to solve the problems of reliability and survivability, environmentally sealed enclosures were used with commercial cards in ruggedized chassis. Other innovative engineering solutions were implemented by Motorola in order to meet the system's performance objectives, while maximizing the use of commercial components and computer hardware. Manny Mora of Motorola observed that the new emphasis on utilizing commercial off-the-shelf technology allowed for greater opportunity for innovation on the part of the contractor, while significantly reducing cost and schedule.

Lesson 8: Effective Army/USAF Coordination and Cooperation

Historically, the Army and Air Force have not been known to exemplify exceptional cooperation, except in times of war. The Joint STARS program was a clear

exception. While the program did not start out initially with strong cooperation, this changed in time due to several factors.

During the 1982-84 timeframe there were significant disagreements between the Army and Air Force project offices as the system specifications were being determined. Bill Kenneally observed that the Army was initially somewhat of an unwilling partner. The Army had wanted its own GMTI program but understood that the options were either a joint program or no program at all. Prior to the finalization of the system specifications significant compromises had to be made as described previously. By 1985 as full scale engineering development proceeded, a spirit of cooperation and effective coordination developed.

Creating effective cooperation between two organizations cannot be accomplished without leadership that is emphasizing cooperation and leading by example. Charles Fowler observed that credit must be given to General James Stansberry, the commanding general at the USAF Electronics Systems Center, his successor, General Chubb, and Brig. General Ed Franklin, the first Joint STARS project manager for the Air Force side of the program following the award of contracts. Since the Air Force was to be the lead on the system, both Stansberry, Chubb, and Franklin understood what it would take to achieve the necessary level of cooperation. To create an environment of cooperation, each concern of the Army's GSM project office was given a high level of priority and consideration. Each critical decision included participation from the Army Joint STARS GSM project office. In addition, the Army project office was kept informed of every important issue. On the Army side, the cancellation of the SOTAS program had been a devastating event. The Army needed a GMTI system, and the motivation was quite strong to make the Joint STARS program a success in the wake of the SOTAS failure.

As the research literature on cross-functional and cross-organizational integration has demonstrated, cooperation is a necessary but not sufficient condition for high levels of performance. What is also needed is the implementation of the proper modes of coordination among organizations. To accomplish this the Army and USAF project offices, Motorola, Grumman, Norden, and Mitre created collocated liaison positions to structurally facilitate and expedite coordination. This mode of coordination was utilized in conjunction with the usual means of coordination through joint meetings, transfer of documents, and direct communication. To illustrate, the Army and Air Force counterparts in the project offices would coordinate with one another and with their counterparts at Motorola for the Army GSM, and Grumman, Mitre, and Norden for the USAF E8 and radar. Mitre would have its systems integration contract personnel at Hanscom AFB with liaison personnel collocated at Ft. Monmouth. Motorola actually had liaison personnel collocated with Grumman at the Melbourne facility.

In addition to the use of collocated liaison personnel the coordination between the Joint STARS GSM project office and Motorola could be characterized as an integrated product team before such teams came into vogue in the 1990's. Allan Tarbell observed that the teams not only included contractor and GSM project office personnel, but also technical specialists from the CECOM labs when needed. The use of collocated liaisons facilitated timely disclosure of problems. From all indications this approach worked effectively.

Epilogue: Joint STARS GSM after the Gulf War

In the aftermath of the Gulf War engineering development continued. In May 1993 approval for the low rate production of five E8C aircraft was granted. The first E8C was completed in December 1993 and made its first flight in March 1994. In addition, in 1993 approval was granted for the low rate production of 12 Medium GSM's. Prior to this decision, a limited user test of the Medium GSM's was successfully conducted. The Medium GSM's were subsequently fielded with contingency forces and used as training equipment.

In September 1994 the Army approved the low rate production of 10 light GSM's following the Force Development Test and Evaluation (FDT&E) that was conducted in August 1994. The Air Force Operational Test and Evaluation Center and the Army Operational Test and Evaluation Command conducted a combined development and operational test of the system from July through September 1995 and an operational evaluation of the system during its deployment in Operation Joint Endeavor in Bosnia from December 1995 through March 1996. Initially, one of the E8A's and the first production E8C were deployed with 13 GSM's and successfully flew 95 consecutive operational sorties and more than 1000 flight hours. The two Joint STARS aircraft and the associated GSM's were deployed again in Bosnia in October 1996 with the addition of the second production E8C in December 1996. In 1996 the Under Secretary of Defense for Acquisition and Technology approved the Joint STARS program's entry into full rate production. However, performance during its combined development and operational test, and the operational evaluation done in Bosnia, did not support a decision to commit to full rate production.

As operational testing, computer upgrades, and other preplanned product improvements continued on the Air Force side of the program, the Army proceeded with its development of the successor to the GSM, referred to as the Common Ground Station (CGS). The CGS would leverage the GSM open architecture and incorporate secondary imagery dissemination and other sensor data from multiple sources including unmanned aerial vehicles, providing tactical commanders with a more comprehensive view of the battlefield. The Common Ground Station represents a major step forward in battlefield surveillance for tactical commanders. Initial operational capability was accomplished in 1999.

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McROCOOLERS

Keeping it Cool on the Battlefield

Case Study of U.S. Army Vehicle Mounted and Dismounted Individual Microclimate Cooling Systems



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Introduction

This case study will examine the success and failure of U.S. Army efforts to supply microclimate cooling to the individual mounted and dismounted soldier leading up to Operation Desert Storm. The U.S. Army has engaged in efforts to provide cooling to the human body for many decades. On and off the battlefield, nuclear, biological and chemical hazards continued to pose a potential serious threat following the WWII era. Thus, the need for soldiers to don protective suits and gear existed. As protective suit materials and design advanced, so did the problem of heat stress and potential heat casualties in battlefield environment and peacetime operations involving hazardous materials. This was and still remains due to the fact, in a sealed environment, the human body can be subject to enormous heat stresses. Protective suit materials do not allow for the natural evaporation processes and radiant heat loss of the human body to successfully provide adequate cooling. Prior to Operation Desert Storm in the Persian Gulf, vehicle environmental systems had been developed to help protect combat vehicle crews from becoming contaminated by outside agents entering vehicle microenvironment from the battlefield, and to allow vehicle crewman to operate in full individual protective gear. Additional cooling is required for the combat vehicle crewman to operate in such an environment with high solar loading and high-sustained work rates. The need for cooling the vehicle mounted and individual dismounted soldier in the desert environment proved to be especially critical. The absence of microclimate cooling available for the individual dismounted soldier may be one underlying factor in the need to perform combat missions in Operation Desert Storm during months of lowest possible heat conditions, thereby reducing strategic and tactical flexibility of the Army. Many attempts to invent practical microclimate cooling equipment for the dismounted soldier have been undertaken by the U.S Army. A vehicle mounted microclimate-cooling system for the M1A1 main Battle Tank was successfully designed, developed and fielded in time for Operation Desert Storm in Kuwait and Iraq. This case study will examine some of the history, technology development, management, successes and failures that took place in the area of microclimate cooling efforts leading up to the Persian Gulf War in Operation Desert Storm.

Origins of Microclimate Cooling

Microclimate cooling involves the regulation of core body temperature and blood temperature to lower the risk of heat stroke and exhaustion. The need for maintaining thermal balance of soldiers in battlefield environment has been known for a long time. The ability to provide individuals with this means has developed slowly, and came into more focus, as the manned space flight program of the United States became a priority. At the time the National Aeronautical and Space Administration (NASA) was in the concept stage, U.S. Army Laboratories in Natick Massachusetts already possessed many of the facilities needed for performing environmental studies and thermal / cooling research for Astronauts to survive in space. During the formation of NASA, a group of scientists and engineers assembled at Natick Laboratories to investigate new concepts and ideas, and a proposal was written to obtain work on the space program. This marked the formation of the Advanced Projects Branch of the US Army at the Natick installation. The U.S. Congress officially formed NASA on October 1, 1958 and the U.S. Army subsequently entered a bid to develop suits for NASA use. Small contracts from NASA were granted to Advanced Projects Branch, Clothing and Equipment Systems Division to develop protective clothing which would support technicians in launch chambers where space modules could be placed to simulate hot side and cool side of the sun. Vincent Iacono, a retired scientist from the original Advanced Projects group, recalls "the suit needed to provide the capability of individual cooling and have sufficient insulation to protect them from the cold". The suit also had to provide survival capability for cooling as well as breathing, from a simulated altitude of 100,000 feet. Natick researchers collaborated with a Milford, Connecticut based contractor called Airlock, Inc. Airlock specialized in Air-Lock connectors and sealed bearings that were been critical components of pressure suits worn by pilots of virtually all high-altitude aircraft since the late 1940's and a established record of high reliability and quality. Airlock was employed to devise a gold plated helmet and electricity component to prevent freezing or condensing during chamber testing. The first Mercury manned space flight came about in 1961 amid the Cold War. During the 1960's, the U.S. Army developed the Thermolybrium Protective Clothing System to provide complete protection from chemical and biological agents as well as nuclear hazards on the battlefield. The Clothing and Equipment System Division that existed under the Advanced Projects Branch at Natick undertook this work. Thermolybrium consisted of a protective helmet, clothing to protect the body including gloves and shoes, and a thermo-electric device for circulating heated, ambient or conditioned air inside the clothing. The design incorporated filtration and cooling to the head and face area. The power supply, while self powered, had to be vehicle mounted. Testing occurred in climatic chambers at Natick to perform fundamental treadmill testing in hot chamber conditions. A key paper was published as the result of studies conducted by Westinghouse Corporation and the group led by a resourceful manager named Leo Spano at Natick Laboratories. This important paper established the fundamental parameters regarding the amount of air required (18 cubic feet) to cool an individual human body.

By 1968 microclimate controlled clothing became available for special applications. In particular, a U.S. Army designed suit for rescue of personnel entering space vacuum

chambers was delivered to the Manned Spacecraft Center in Houston, Texas. In addition a (thermal) Environmental Protective ensemble for protection of personnel checking the Saturn V rocket booster was delivered to the Marshall Space Flight Center in Huntsville, Alabama.

Asynchronous Development of Microclimate Cooling

As conventional warfare development evolved under the potential threat of conflict in Cold War era northern Europe, coupled with advancements in cooling fueled by the manned US space program, the Advanced Projects group engaged in basic and applied research. The Army was always looking for smaller, lighter more potent power systems. The Advanced Projects group reported investigating fuel cells, thermo-electrics and nickel-cadmium battery performance in addition to, and in conjunction with, the possibility of cooling the individual ground soldier. Most of the work was designated as special applications, however rather than microclimate cooling. With the advent of the jet airplane, British developments led to an undergarment configuration allowing forced air to circulate through tubing held next to the body to provide supplemental cooling for individual air crewman. Later, informal requests were made to U.S. Army Advanced Projects during the Vietnam conflict, to devise an air distribution system to cool helicopter pilots in the theater of operations. Prototypes were designed utilizing a blower system and sent to Vietnam. However, no written requirements were drawn up or formal program existed for this purpose. Work in the microclimate cooling area in the Army depended on seed money, collaboration with related projects and ongoing interest of personnel in solving difficult cooling problems.

The first tangible individual soldier microclimate cooling application came in cooling systems designed for U.S. Army Explosive Ordinance Disposal personnel, with microclimate cooling researcher Joseph Cohen as project officer. Developments in microclimate cooling were incorporated into prototype EOD suits called Protective Outfit Toxicological Microclimate Cooled suit, or POTMC. POTMC incorporated special zipper seals, a sealed helmet design that still allowed for mobility and wide visibility, and a counter flow air system borrowed from the space suit prototypes. U.S. Army NBC Protectorate branch at Edgewood Arsenal, Maryland, developed a compatible filtration system for the EOD suit. Extensive testing of the portable backpack mounted EOD cooling system was performed at facilities in Yuma, Arizona and Dugway Proving Grounds in Utah in addition to Natick Laboratories. All chemical agents testing involving the EOD suit was performed at Edgewood Arsenal. Prior to the EOD suit, cooling was limited to ideas or piecemeal testing. In fact, EOD suit was the first soldier mounted cooling assembled and tested as complete system by the U.S. Army. Unfortunately for the regular ground soldier, EOD applications differed from the necessities of infantry soldier functions. EOD requirements were very specific in that a highly impact resistant, high visibility helmet was needed. Unlike explosives personnel, the ground soldier needed to be able to run, jump, operate weapons systems, carry heavy

gear, and a myriad of other functions. Advanced Projects researchers concluded that the only way to maintain the soldier in some thermal balance is by means of cooling the individual (as opposed to cooling the immediate surrounding environment); this is the approach that concepts involving individual cooling of the dismounted soldier were based upon. When essential requirements of the individual dismounted ground soldier were compared with those of the special applications prototype designs, the bulk and weight of potential cooling system would clearly be very encumbering for the ground soldier. Therefore, the feasibility of cooling for the individual ground soldier was perceived as not practical unless ground rules for warfare changed dramatically. In short, the Advanced Projects team saw waiting for further technological progress as the best alternative.

With no further progress on the individual dismounted soldier applications, Army researchers, then under the leadership of Vincent Iacono, also undertook other special applications projects. The U.S. Coast Guard approached the Army labs to assist with problems encountered when dealing with toxicity. The military filters being used on protective gear utilized by the Coast guard did not satisfy their particular requirements of internal breathing and maintenance. Advanced Projects created a system that had the ability to operate as a closed system and transition to an open system routed through the protective filter. Closed cryogenic backpacks were contracted by the Army to be developed by the Garrett Corp. Other development work was also done on behalf of the U.S. Environmental Protection Agency. Fort Detrick, Maryland also employed Advanced Projects personnel in developing impermeable protective clothing with air capability for laboratory use.

Challenges in Cooling the Individual Dismounted Soldier

Throughout the Cold War era and even today, keeping the individual protected from nuclear, biological or chemical (NBC) contamination in full contamination suits and cool enough to operate without suffering serious heat stress is a significant concern. The U.S. Surgeon General Office, collocated at Natick provided assistance with ergonomic studies and physiological monitoring as well as test planning. U.S. Army Research Institute of Environmental Medicine also worked closely in basic testing of the heat stress limits, controlled chamber testing and experimental design using environmental chambers available at Natick Labs.

Given the cooling problems encountered by soldiers in normal climates, operating in an NBC environment under desert conditions posed an extreme threat of unsustainable heat loading. Preventing heat stroke and heat exhaustion in the individual soldier was viewed as a medical constraint, not a soldier comfort issue.

The Army did recognize that microclimate cooling produces additional benefits:

1. INCREASED OPERATING TIME IN HIGH HEAT ENVIRONMENT
2. INCREASED OPERATING TIME IN NBC PROTECTIVE SUIT
3. REDUCED PERSPIRATION → LOWER WATER INTAKE REQUIREMENTS
4. SOLDIER COMFORT

In the case of cooling the individual ground soldier, no further progress was made from the 1960's to the 1980's. The three main technology concerns were (and remain):

- 1. POWER**
- 2. WEIGHT**
- 3. BULK**

The challenge to develop an available power source that was small and light weight enough to be practical for the dismounted soldier is the foremost obstacle. A microclimate conditioning unit for dismounted soldier must, at a minimum, meet a variety of criteria including low weight, ease of supply, compatibility with other backpack and infantry gear configurations, reliability, and preservation of camouflage, safety and chemical protection of the soldier. The standard issue chemical protective over garment throughout the 1960s to 1980's featured permeable, charcoal impregnated suits. Permeability offered a tiny amount of heat transfer, at the expense of being vulnerable to agent saturation. Consequently, Army researchers were interested an impermeable chemical protection suit that would improve soldier protection. However, impermeable materials only compounded the problem of heat stress. What impermeable materials gained in protective value was lost due to near complete lack of heat dissipation. To help attack this dilemma, U.S. Army researchers Fred Allen and Mark Holtzapple prepared a detailed technical paper that outlined heat removal requirements, physiological factors and a long list of microclimate cooling options. Some examples included Endothermic Reaction, Peltier Cooling, Solid and Liquid Absorbent Cooling, Air-Cycle Cooling, Stirling Cycle and Vapor-Compression Cooling. A scientific approach was used to compare the various energy sources, generators, pumps, overall efficiencies of each method, and ranked the feasibility of the many proposed micro-cooling options. As an example, vapor compression cooling was a well-established and understood refrigeration technique with many commercial applications unlike many of the other options. Results proved nearly all methods unacceptable for all but Solid Absorbent, Air Cycle and Vapor Compression. Still, all had drawbacks in managing high heat loads, noise, weight, size or other logistical factors. For both the vehicle mounted and dismounted soldier applications - problems overcoming the power, weight and size constraints continued to plague the researchers efforts. Physics was simply against a

practical battlefield solution with known methods and current technology available at that time.

Cooling on board with Vehicle Mounted Microclimate Cooling

Prior to the 1980's, there was already concern regarding thermal stress on individuals exposed to hot environments in closed crew compartments. Air vehicles such as the AH-1G Cobra Helicopters were shown to be particularly vulnerable to what was termed a "hot house" effect even in moderate air temperatures. Additional work on thermal stress generated inside infantry combat vehicles pointed out need for further evaluation as requirements for chemical protection was added to hot environments and closed compartments. The M1 Main Battle Tank was to undergo planned improvements, part of which included augmenting the cooling of crewman and providing NBC protection. The original M1 tank was designed to use air-cooling for the express purpose of keeping the electronic instrumentation cool. In light of heat stress identified as a hazard to crews operating the US' main workhorse tank, a Block 1 follow on improvements program called for existing air to create positive "overpressure" inside the cockpit. This compartment overpressure of forced airflow was designed to provide collective protection for the entire crew against infiltration of chem-bio agents. In September 1980, crewman dressed in chemical protective clothing performed routine exercises during simulated tank exercises in desert conditions of Yuma, Arizona. Results were unambiguous, showing that tank crewman could not endure long exposures to closed, unventilated compartments. Advanced Projects underwent a name change to the 'Special Projects Section' under the Armor and Special Projects Branch of Individual Protection Directorate leadership passed to Vincent Iacono in 1981. The small group of Natick researchers kept microclimate cooling ideas afloat mostly on seed money and related projects. Vincent Iacono and Joe Cohen, of Special Projects Branch's Individual Protection Laboratory, were involved with 1980 testing which determined that liquid coolant circulated through vests worn by the soldiers significantly increased the tank crewman tolerance levels and allowed them to perform tank operations under extreme heat conditions whereas without the cooling they became incapacitated in a short time. These test simulations also conclusively demonstrated the need for auxiliary cooling of crew compartments for operations in hot or contaminated environments. Not long afterward, the Commanding General of the U.S. Army Training and Doctrine Command (TRADOC) "directed that an evaluation of the effectiveness of air shower and vest auxiliary cooling be carried out" according to a technical report by the U.S. Army Research Institute of Environmental Medicine (ARIEM). A M1E1 battle tank was modified for chamber testing at Natick Labs. Two 4-men tank crews from the 2nd Battalion, 6th Cavalry, Ft. Knox, Kentucky participated in the testing. Commanders at the time were apparently in favor of air conditioning the tank quarters as part of collective protection (filtering and cooling for the whole crew as opposed to cooling each individual separately). This approach can be loosely termed as macroclimate cooling. It was quickly determined that the weight, bulk and expense of both cooling and circulating

ambient air into cockpit solely using refrigeration was prohibitive and impractical. With tank crewman under high heat conditions compounded by various stages of MOPP gear (NBC protective suits), the demonstration made clear that an individual cooling configuration was necessary and desirable.

Combat Vehicle Crewman Air Vest

The U.S. Army Tank and Automotive Command (TACOM) located in Warren, Michigan provided funding to the Special Projects Branch under the M1 "A1" improvements program to provide auxiliary cooling to individual crews. This effort was the only fully funded program that resulted in the fielding of a US Army standard issue microclimate cooling system through the time of Operation Desert Storm.

Liquid cooling proved a highly efficient cooling method in the case of combat vehicle crewman. Nonetheless, liquid cooling possessed disadvantages in the vehicle-mounted configuration. Liquid coolant adds weight to the vehicle as well as the complexity of the hoses and vest attached to the individual tank crewman. An additional problem was the risk of leakage. Depending on the coolant material, for example propylene glycol (antifreeze coolant) was experimented with previously; a leak could spill hazardous material into the closed compartment of the M1A1 Main Battle Tank. Finally, liquid coolant contaminated by chemical or other agent raises the additional problem of how to vent or safely dispose of liquid from the tank environment once it has become contaminated. The most practical and cost effective solution to the combat vehicle crewman cooling challenge was to develop an air vest. Numerous major advantages exist for air utilized as coolant in an air vest configuration. First, the M1A1 was already equipped with a compressor running off the turbine engine that already produced humidified and cooled air. This eliminated the need for a separate power source and compressor. Second, liquid cooling tubes in a vest were prone to leakage whereas air leakage in a vest was considered an advantage because it created positive pressure. Positive pressure is useful in keeping contaminants from entering the open cooling system. Air is certainly easier to come by in remote desert combat than a specialized liquid, and utilizing the readily available source already part of the M1 saved cost, weight and bulk. From a safety standpoint, a third advantage was that contaminated air is much easier to vent from a closed environment of the M1 crew compartment. Fourth, even with the loss of cooling capacity, just circulation of air against the body enhances natural evaporation process.

A formal program was undertaken with requirements from TRADOC, funding through the TACOM office under the umbrella of M1A1 Main Battle Tank improvement program. The microclimate cooling group was given a target to meet by the user (represented by Armor School, Ft. Knox, Kentucky) and was tasked with coming up with a concept for the intended application - with close support granted by the Testing and Evaluation Command (TECOM), NBC Protection Directorate, U.S. Surgeon Generals Office, Army Materiel Systems Analysis Activity (AMSAA), ARIEM as well as outside contractors involved as the project progressed. Barry Decristofano, recalled meetings

were held which integrated the myriad of branches involved in the program effort. These meetings were referred to as TWIG, which stood for Task Work Integration Group. This integrated mix of customer; stakeholders and persons both directly and indirectly involved with development facilitated good cooperation and communication as well as progress monitoring and requirements oversight functions. It is noteworthy that TWIGs existed as a good approximation of what is now referred today as Integrated Product Teams, now widely regarded as highly effective organizational structures for complex technology based projects.

Nonetheless, it is apparent that despite being a formal program, the Combat Vehicle Crewman air vest did not go through the conventional research and development process associated with many formal Army programs. The air vest program started out as a concept on the laboratory bench at Natick Labs and swiftly progressed into prototyping and production – largely driven by the high profile TACOM improvement program, steered by goal of keeping the tank crew safe and cool for 12 hours at a time, and using testing information generated by applied studies on metabolic load to determine air flows. The early stages of the air vest project remained largely a combination of in-house development and prototyping with testing, evaluation and collaboration occurring with the organizations mentioned above. The air vest would consist of a one size fits all polyaramid (fire-resistant) vest material with hoses fastened by Velcro into the material. Compression molded ABS plastic manifolds routed airflow to cool around the front and rear torso, and through hoses attached to the top and passed through a circular manifold cooling behind the neck. Small holes designed into the top (neck) hoses allowed air to partially escape for the purpose of blowing air into the MOPP gear if crewman were wearing their protective suits. This had the added benefit of providing positive overpressure as well.



Combat Vehicle Crewman Air Vest
Photo courtesy of U.S. Army Soldier Systems Center

The lead project engineer for the air vest program, Tom Tassinari, joined the microclimate cooling team in 1981. Tassinari oversaw what was “the” critical requirement for a connector to interface with hoses to the standard issue protective mask used by tanker crews. No compatible connector existed to connect and regulate a tank mounted cooling system. Such a connector was required to take air coming in to cool the crewman’s body and simultaneously divert a fraction of that air into the protective mask for the soldier to breathe. This also needed to be adjustable enough to accommodate

different heat conditions and metabolic rates. Tassinari designed and worked on development of the connector at Natick Labs while collaborating with NBC Protection Directorate in Edgewood, Maryland to ensure design safety, function, NBC engineering requirements compliance and physical compatibility with the NBC equipment. Initial fabrication and prototyping of the all-important plastic connector took place in-house at Natick Labs. Later design changes were necessary when Airlock, Inc of Connecticut ran into problems with injection molding the prototype connector design for production. Barry Decristofano, chemical engineer at Army Natick Labs recounted the problems. A problem arose whereby design changes for the manufacturer of the Y-connectors impeded production and shipment of connectors for assembly by the main contractor. This critical delay prevented scheduling assembly with the air vest hoses before delivery of the final product was required. The deadline, for shipping final assembled air vest to tank manufacturer, was in danger of being breeched. Management decided on a workaround which re-routed shipment of air hoses and the Y-connectors to US Army Natick Labs. Advanced Projects personnel at Natick performed final assembly on weekends. The air vests were successfully assembled at Natick and shipped to the tank manufacturer on time to meet the M1A1 project schedule. This level of flexibility, unconventional resourcefulness and dedication of Army microclimate cooling team members appears to have been a thread throughout the history of micro cooling efforts and clearly contributed to the final success of the air vest program.

All air vest team members interviewed for this case study reported a good working relationship with Airlock, Inc as well as the company contracted as the sewing and vest integrator. The Project Officer and Lead Project Engineer both cited many reasons for the success of air vest program. Among these reasons were good starting concept and engineering feasibility, support from the Armor School within TRADOC, frequent and productive collaboration with TACOM and General Dynamics Land Systems (manufacturer of M1A1), high visibility of the M1A1 improvements program. In addition, other factors were high team member quality and co-location at Natick Labs. Co-location with ARIEM was cited as particularly helpful. Also, the combined nature of the development testing and operational testing (DT/OT) phases enabled the program to be carried from concept to production and fielding within the relatively short time constraints of the M1A1 improvements – just a few years.

Retired M1A1 Heavy Main Battle Tank master gunner Randy Mitchell, of the Armor School in Ft. Knox, Kentucky confirmed that during his combat duty the crewman air vest was indeed successfully fielded and part of standard issue crewman outfit for every version of the M1A1 in Operation Desert Storm. Mitchell reported its use was primarily during periods of operation when the tank was moving and the main crew hatch needed to be secured closed for extended periods of time. Securing the hatch may be due to existing weather conditions, a precaution taken when alert for chemical or biological hazard, or during direct combat. During Operation Desert Storm, which occurred during winter months, full time use of the vest was not required. Mitchell reported that some tanker units chose to utilize the air vest while others did not during the combat operations in Kuwait and Iraq. The vest was stored in a on-board storage locker when not in use and worn over the undershirt and under the rest of clothing layers when utilized by crew members. Mitchell expressed that the design was relatively simple and foolproof in

nature and was readily accepted by crewman in general - especially when closed cockpit temperatures rose toward 140 degrees Fahrenheit.

Individual Microclimate Cooling for the Dismounted Soldier

Finding a solution to the problem of cooling the individual dismounted soldier has proved to be an enormous challenge and struggle throughout the history of microclimate cooling efforts. Years of research, lack of funding, low technology readiness levels, absence of user driven requirements, low priority of heat stress in terms of survivability and lethality concerns of the Army combined with unfavorable physics problems have all resulted in no practical cooling system solutions for the soldier on the ground. It is notable that nearly a decade and a half after Operation Desert Storm, the challenge still largely remains – though progress is being made. The technology simply does not exist to practically cool the general infantry soldier with a full microclimate conditioning system. A soldier carrying a backpack, communications equipment, NBC protective gear, rations, weapons and ammunition simply cannot carry additional weight and bulk necessary to significantly cool him/herself with available microclimate cooling technology. A backpack mounted microcooling system has yet to be demonstrated that has not interfered substantially with the backpack individual infantry soldiers normally wear to carry personal equipment. Tactical issues such as quiet operation and reduction or isolation of thermal emissions remained minor ongoing obstacles as well. The power requirements for significantly cooling the dismounted soldier have been far too high to trim the weight and size of microclimate cooling equipment sufficiently to allow soldiers to run, jump, crawl, hide, operate weapons or otherwise perform tasks critical to maneuver successfully on the modern battlefield. The questions we may ask are why has there been no solution to this problem, what was the US Army doing to address the heat stress and potential heat casualty problem in terms of microclimate cooling research and development and why was there no solution available for the desert warfare encountered in Operation Desert Storm in 1990. Reasonable question arises for why the Army was so unprepared to have soldiers operate during extreme summer months in the Persian Gulf, as well as what has the Army been doing about finding a solution to a problem that is predictable, present and not altogether unknown or new. It is interesting to note that the cold war battle plan of the U.S.S.R. in Northern Europe was to scatter chemical agents in different areas, forcing U.S. troops to don full MOPP gear. This strategy counted partially on the difficulty of operating in this environment, one component being the lack of preparedness of troops to deal with heat stress. To be fair, this operational vulnerability is common to all militaries that undertake preparation for combat in NBC environments. However, the strategy of the U.S. Army appears to be grounded in the attitude that it is better to stay out of combat and avoid situations where operations in NBC contaminated environment and high heat stresses are encountered. There is certainly good logic in the desire to avoid hazards but this strategy does little to counter the reality that fighting in these two conditions are both very possible and perhaps probable. Operation Desert storm served to underscore each of these assertions.

Perhaps the good news is, despite the uneven commitment of the US Army toward solving heat problems encountered by the individual soldier in high heat climates and operational conditions, efforts to solve the problems have still been made. The very same group of microclimate cooling researchers in Special Projects - involved in tackling heat and cooling problems for various other federal agencies, various branches of the military and vehicle mounted Army customers - have been working on the problem for a long time, despite many obstacles. Through the course of many interviews with Army researchers and civilian contractors, it became clear that no conspiracy to avoid addressing the cooling needs of the individual Army soldier has been afoot. Rather, the seemingly intractable nature of the problem intersected with the relatively low priority placed upon heat stress appears to be the crux of the situation and largely responsible for the absence of a technological solution.

Individual microclimate cooling for the dismounted soldier, contrary to its vehicle-mounted cousin, did not have the benefit of an officially funded program to bolster development. Building off of basic research, conducted during the early days of the manned space flight program, coupled with entrepreneurial management from Leo Spano and Vincent Iacono served to carry on more advanced microclimate research at Natick Labs in the absence of direct funding. Dr. Fred Allen, a Natick microclimate researcher recalled the funding situation. Funding for basic or applied research was available and could be applied to microclimate cooling as part of project money allocated to the Special Projects section. However, in order to obtain funding to take a dismounted cooling project out of applied research, formal user requirements needed to be presented by potential users (e.g. the Infantry School or the Chemical-Biological School from within the Training And Doctrine Command). User requirements enable funding to be distributed for development of demonstration units and prototyping. No user requirements existed. On the flip side, Allen indicated that difficulties existed in understanding exactly what the individual soldier wanted. Often times the user did not know exactly what they wanted so researchers attempted to introduce new technology to users by bringing examples and ideas in front of the user. It was helpful for researchers to be able to bring practical demonstrations to the users for the purpose of "selling" potential users on benefits. This effort was to show that a particular microclimate cooling concept could possibly fill a need of the individual dismounted soldier in the field and thus generate a formal requirement. Tradeoffs would be discussed directly with potential users in terms of how much cooling soldiers wanted versus how much weight they indicated willingness to bear.

Despite effort of Natick researchers to expose concepts to potential users, absence of requirements based on a specific "need" request from the Army effectively prevented the direct funding of individual cooling for the dismounted soldier application. This ongoing resource obstacle significantly increased the difficulty of generating sufficiently advanced physical demonstrations of new cooling technology. Therefore, research was relegated mainly to piggybacking on funding from related projects, Small Business Innovative Research (SBIR) grants and other indirect research opportunities. At times further research could not be continued due to lack of funding.

The biggest challenge facing dismounted soldier cooling remained the power source. Not to be deterred, research continued in the mid 1980's with basic research supported by a group at the University of Washington attempting to harness the Stirling cycle to provide a power source small and lightweight enough to be carried by a soldier but still capable of producing the amount energy required to adequately cool the body. A company called Stirling Technologies in upstate New York was contracted (in addition to the Washington research group) to develop a functional Stirling engine. The Stirling cycle refers to a process of expanding and contracting a gas (in this case helium was used) within series of cylinders in order to produce work on the surroundings. A Stirling engine, it was hoped, could provide an efficient, regenerative process for powering heat removal from the body by acting as an external combustion engine. The engine was intended be part of an air cycle cooling system. One problem incurred was that the Stirling engine required an additional battery (and therefore more weight and space) to start the cycle. The two contracts did yield one early functional Stirling engine. This effort was ultimately not successful. At this time very little proof of concept work existed in microclimate cooling. A different concept altogether - identified in the 1983 report, Microclimate Cooling Options for the Individual Soldier, later happened to arrive separately unsolicited from a small private company in what was called a Peltier backpack. This featured a liquid cooling system in which electrical current passed through different types of semiconductors creating either a hot or cold junction. Water flowed past the cold junction and circulated through a vest worn by the soldier to provide cooling. Interestingly, the process could be reversed and used for heating purposes. Unfortunately, while the Peltier system had the singular advantage of no moving parts, and could operate in any orientation without generating noise or vibration, the Achilles heel again turned out to be the need for heavy batteries to supply the electricity and also relative poor efficiency. This method was rejected as a practical dismounted cooling alternative.

Between 1985 and 1990, Dr. Fred Allen summarized, the state of microclimate cooling research for the Army consisted of 6 researchers within the Individual Protection Directorate. Allen, who took over managing Special Projects, related that approximately half of his time was devoted to projects advancing microclimate cooling. While Barry Decristofano stewarded the air vest program into production runs, a Massachusetts company named Foster-Miller was contracted to explore vapor compression as a viable approach to the dismounted soldier cooling challenge. Miniaturization of components made vapor compression a more viable cooling method than in previous times and became the leading candidate for satisfying the individual soldiers needs for compact, lightweight efficient cooling with low power consumption.

The Army awarded Foster Miller funding to create a backpack mounted cooling system - the Individual Microclimate Cooling System, or IMCS for short. Specifications were provided by Nuclear, Chemical and Biological Command (NBCCOM) to solve individual cooling problems for EOD and perimeter guards providing security to chemical/biological sites. These personnel need to wear full MOPP suits and tend to be working in more localized situations than the general infantry - thus a backpack mounted

cooling system was more feasible. The IMCS project began in 1987 as an electric powered vapor compression unit designed into a backpack mount with a brushless DC motor. In the midst of contract fulfillment and a demonstration unit being produced by Foster Miller, turnover occurred of technical project officers in the Army overseeing this effort. The incoming project officer determined that the IMCS demonstration unit was too complicated and employed too many electronics. By 1989 the Army called for Foster Miller to modify the IMCS. A second generation IMCS was constructed reusing many of the parts of the earlier model; however the system was now belt driven by a small internal combustion engine adapted from a 2 cycle hedge trimming motor and 4-cycle model airplane engine modified with cooling fans and miniaturized carburetion controls. The energy source chosen to fuel this engine was JP8, a widely available kerosene gas turbine fuel used by the military. A major concern surrounding the design of the IMCS was the presence of internal combustion in area of explosive atmospheres. To help reduce weight and bulk, the IMCS incorporated a new lightweight aluminum heat exchanger created by Modine Manufacturing with high coefficients of heat transfer in very small package. An improved brushless motor, a compact water pump modified from a design of fish tank water pumps, and a borrowed design of cylinder with piston in a special lightweight housing for a compression system made it into the second IMCS. Thirteen additional demonstration units were yielded from contract with Foster Miller, with the Foster Miller components married to vest materials provided through the Army. Roger Demler, a manager of the IMCS project for Foster Miller recalled the particular problem with development for limited production projects such as the IMCS was the scarcity of seed money for robust prototyping and adequate production tooling required to make production cost effective and take advantage of best technology. Limited field trials of the IMCS units were taken but never resulted in a backpack-mounted system that could warrant user support based on strict needs requirement. Not surprisingly, the contractor reported that the IMCS failed to win final customer support due to initial high cost needed for production of such a unit, relatively limited customer base and concerns over complicated design. In general, practical size, weight, noise and other physical design limitations - proved to be restrictive in terms of funding and ultimately spelled the end of IMCS. While the nature of the technology involved was a mix of new and existing, IMCS still did not represent progress to the point that the dismounted soldier was interested in a realistic way. Foster Miller reported a cross-functional team approach to the IMCS and numerous interactions with the Army including conferences to facilitate information sharing, concepts and understanding of needs and technological feasibility. This is an important note when considering the varied and loosely structured composition of microclimate cooling evolution.

The Army organized additional fundamental research in personal cooling research according to documentation in April 1988. ARIEM, in collaboration with what became called the U.S. Army Natick Research, Development and Engineering Center - completed a study and published report that tested the effectiveness of a prototype hybrid air-liquid cooled vest. The aim was apparently to utilize the advantages of both liquid cooling and air-cooling in combination to create adequate cooling for soldiers under heat stress. The hybrid microclimate cooling garment was constructed of two parallel channels one for air and one for a propylene glycol-water solution. The concept intended to provide a more

“averaged” coolant temperature on the skin than either of the two coolants could provide separately. The technical report indicates that combat vehicle crewmen who “need cooling for both mounted and dismounted activities” considered the hybrid design for potential use. This reflects the increasingly mobile nature of the infantry soldier and the ever-present threat of chemical or biological warfare on the battlefield. Five soldiers experienced this hybrid design in treadmill tests under full MOPP IV chemical protection suits. Minor problems in comfort and design were attributed to this hybrid design.

The era approaching Operation Desert Storm did contain microclimate cooling projects moving forward to some extent. Further attempts were made through efforts of Natick microclimate cooling researcher Brad Laprise to create a more successful Stirling engine design resulting in contracts for prototype. The Army issued a contract to Foster-Miller to develop a microclimate cooling system for a program named STEPO, short for Self-Contained Toxic Environment Protective Outfit. This outfit, intended to protect Army technicians from toxic and hazardous exposures, featured a battery powered vapor compression cooling system to be portable, backpack mounted. Again, this system did not satisfy the needs of an infantry soldier so was not directly applicable to the dismounted infantry soldier.

Microclimate cooling efforts in the late 1980's and the beginning of the 1990s also included various other contractor designs for ice cooling systems. The US Army looked at a vest design from Canadian developed ice cooling system. Testing went forward on Army depot workers to relieve heat stress. An ice-cooled system called PICS, for Personal Ice Cooling Unit, was tested on Johnston Atoll in the South Pacific. Subsequent to Operation Desert Storm, engineer Roger Masadi from the Life Support System Division of the Individual Protection Directorate worked with fellow Army researchers to produce an “Evaluation of Five Commercial Microclimate Cooling Systems for Military Use. Four of these units were utilizing ice portable cooling systems. Laboratory and field testing was conducted on US Army EOD personnel, Air Force firefighters and Army decontamination personnel.

H
M-40 CHEMICAL
PROTECTIVE MASK

Behind the Mask

Case Study of the U.S. Army M-40 Protective Mask Series



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Introduction

The U.S Army M-40 series protective masks are rooted in the M17 mask. The M17, adopted in 1959, replaced the M9 mask in its role as the main infantry mask used to provide protection of the eyes and respiratory system from biological and chemical agents. A protective mask is essentially a device designed to cover the face, and protects from inhaling toxic airborne substances or coming into contact with liquid agents. The M17 was the first general issue U.S. mask to incorporate a voice transmission device. This device, called a voicemitter, assisted the soldier with improved voice transmission capability. This mask made use of natural rubber compound, had 2 cheek-mounted filters, a nose cup and two triangular shape rigid eye lenses. Further development yielded an improved version introduced in 1966 as the M17A1. This modified version featured a drinking tube, which allowed the soldier the advantage of drinking fluids in a contaminated environment. By the 1970s, the Army inventoried four standard masks – the M17A2, M25A1, M24 and M9A1. The M25 Tank mask series was used to satisfy the special needs of the tanker environment. The M24 Aircraft mask, very similar to the M25A1, could hook into an airframe mounted air purification system but also accommodate an external filter. The M9A1 was retained as Mask, Special-Purpose, M9 due to its utilization in chemical surety units. Unfortunately, the group of different masks generally used only a few common parts. In addition to the logistical burden incurred, this proved expensive for the Army to acquire parts and maintain spare masks. In response to these concerns, the Army endeavored to create a common-mask system in order to reduce logistics and expenditure. However, the main impetus for the development of a new protective mask was to provide improved fit and protection over the standard family of masks offered. These initiatives culminated in the M40 series protective mask. More than 15 years and 3 mask development projects were to become necessary before initial fielding of the M40 occurred in 1990 during Operation Desert Storm. This case study is an effort to document the circumstances and considerable technology management complexities arising out of the effort to design, develop, test and produce an acceptable evolution from the M17. This effort required simultaneously meeting needs of cost reduction and simplified logistics.

From the Beginning....

The M40 series of protective masks were born out of several "X" development programs dating from the early 1970's. These programs were labeled with XM-- prototype designation. With the goal of creating a common-mask system, exploratory development was initiated with the launch of the XM29 program in 1972. The purpose was to establish whether the design concepts could satisfy what the soldier wanted in a new mask. In September 1975 the Army awarded an advanced development contract to the

California based Sierra Engineering Company. U.S. Army personnel from Edgewood Arsenal, Maryland worked closely with Sierra to advance concepts and produce quantities of masks for use in testing. Edgewood Arsenal served as a hub for the XM29 program. The Directorate of Development and Engineering, the Technical Support, Product Assurance, and Procurement Directorates as well as the U.S. Army Biomedical Laboratory each guided or supported the project from Edgewood. On a continuous basis, Army personnel traveled to Sierra facilities in California to assist working out technical issues or other problems. This type of collaborative role played by Edgewood would continue throughout the XM30 and XM40 programs.

A major goal of the XM29 program was to simplify the design as well as the assembly and production techniques. The M17 mask production process was well established yet involved a high number of assembly steps. The Army and Sierra Engineering pursued a single mold construction that attempted to depart from the complexities of manufacturing existing in previous masks. Early prototype testing took place at the U.S. Army Cold and Tropic Region Test Centers, the U.S. Army Human Engineering Lab and in addition at the U.S. Army Aeromedical Research Laboratory at Fort Rucker, Alabama. To achieve this new uni-mold design, injection-molding technology was adapted and developed to use with a revolutionary new silicone material. Silicone offered potential advantages over natural rubber with its compliant character allowing for better facial fit. Silicone also demonstrated no permanent set and remained flexible under extreme cold conditions. Another significant characteristic was that silicone materials performed very well under high temperatures and do not age or crack.

For any protective mask to be effective, it must create an airtight seal around the face. The XM29 mold design process allowed a better seal design utilizing an inward-turned peripheral flap molded inside of the mask. This design feature helps ensure fit around the entire face of the soldier. At the time, however, silicone posed major technical challenges in material development and process design. Silicone did have vulnerability to liquid agents and decontamination chemicals. Silicone also tended to scratch easily. Special coatings were required to mitigate these problems, with considerable technical effort undertaken by the Army and its contractors. Subsequently, a chemical resistant coating known as Viton was added along with a scratch resistant coating on silicone face blank to overcome these challenges. However, coating technology was still not adequate at this early stage to meet testing, operational and producibility targets.

The M17 mask featured numerous buckles on the straps used to keep the mask snug to the soldiers' head. This design required a separate buckle assembly process to be performed individually during production. The XM29 team focused major effort to streamline the manufacturing process by instead inserting 6 buckles simultaneously into place during the injection molding process. This made novel tooling design and technological development essential, as this approach had never been previously attempted.

The M17 was a departure from traditional canister filter design found in all previous U.S. Army protective masks, being the only mask without a canister. Filters were located

inside of the mask itself requiring soldiers to remove the mask, undo and remove rubber buttons before inserting a new filter. This maneuver was time consuming and simply could not be performed in a contaminated environment. The M17 mask filters also suffered from maintenance problems in the field. The XM29 project, therefore, returned to the canister design and benefited from NATO standard thread compatibility. Essentially an extra round of thread was added to improve filter canister engagement and overall reliability. Filter canisters could be mounted on either cheek – allowing the soldier to adapt for right or left tasks such as sighting of weapons systems. The screw mount not in use had an insert that served as a voicemitter in addition to the front voicemitter. An outlet valve assembly design was also included in the XM29. The XM29 series mask was developed in four versions: combat, armor, aviation and special purpose.

Sierra Engineering Company was sold to Scott Aviation in 1978. Added to the chemical bonding, single facepiece silicone and injection molding hurdles, this change in ownership and subsequent relocation of facilities from Sierra Madre to another location within California caused additional management and operational challenges to the program. The XM29 also encountered lens-coating problems. The eye lens tended to “frost” and failed required light transmittance tests. Ultimately the XM29 program was terminated in October 1979 because the optical quality of the eye lens could not be sustained.

Termination of the XM29 did not alter the Army need for or determination to obtain a new mask. During the same month as the XM29 program ended, the XM30 program was instituted. The objectives of the XM30 mask program remained basically the same as the XM29. Scott Aviation was retained as the primary contractor from the XM29 to the XM30. The silicone face blank was retained and an adhesive attached flexible polyurethane eye lens design was pursued. This large flexible lens provided improved visibility over the M17. The major technological challenge of the XM30 was the chemical bonding of the dissimilar materials, intended to replace the mechanically attached method utilized by the M17 design. Developing a bonding process to fuse silicone with the urethane material proved difficult and time consuming. Tooling difficulties were a significant logistical and technical challenge. The new bonding process had to withstand and maintain bonding seal in all operational and climatic conditions. Nine hundred XM30 masks were produced.

Testing took place at five developmental test sites (including mask storage and climatic tests) and four operational test sites (infantry/user tests). The XM30 program developed and tested several versions including an Infantry Mask, Armored Vehicle (“tanker”) Mask and an Aviation Mask. The Army conducted mask interface tests and evaluations with over 100 different military systems including sighting devices and use with communication handsets. Following the evaluation of the test results, the XM30 program was terminated in July 1982. The termination cause was specifically due to its performance in Army “Common Soldier Task” test evaluations. The XM30 mask had a statistically significant advantage over the M17 mask, when worn by a soldier in sighting and firing of the M16 rifle. However, no advantage was shown in tests involving all

other Common Soldier Tasks. The decision was made by the Army not to purchase the XM30 mask because it did not offer operational advantage or improvement over the current family of masks at that time.

The XM30 program suffered heavy public criticism from Congress. In May of 1982 US Senator William Proxmire gave the XM30 program a "Golden Fleece Award."

It is worth noting that the chemical bonding of the urethane lens to the silicone face blank was eventually solved. The U.S. Navy and U.S. Air Force did appropriate the XM30 which became their standard mask – designated the MCU- 2/P. To say the XM30 program was a failure is not entirely accurate as it was an operationally effective mask and represented technological advancement in protective mask materials, tooling, design and production technology.

Product Development Outcomes

The XM29 and XM30 programs clearly had difficulty matching the needs of the U.S. Army for a new, improved mask with the technology required for developing such improvements. Studies tell us, and indeed common sense suggests, that a defense technology development project is more likely to succeed when the customer expectations and needs, are matched by the product developers resources – technology, engineering and production knowledge as well as sufficient time and money to achieve the project targets. Early user evaluation was seen as lacking in the XM29 program, which hindered a successful outcome of the development program. Early user testing, involving soldiers, in the XM29 and the XM30 programs could have improved the chance to yield a protective mask determined as acceptable in operational testing and having an operational advantage over existing masks. This was a factor leading to the Golden Fleece award for the XM30.

Overcoming problems matching new technology development with customer requirements is a balance of risk tolerance, progression of research and development, and overall management of technology. These problems are inherent in new product development. The timing and interplay of these elements is a critical component of the successful launch and ultimate success of a program. In the case of the XM29, the U.S. Army desired a mask that government and industrial contractor technology resources were not adequate to deliver. Therefore, development was not able to meet all the performance, schedule and cost objectives. This resulted in a mask with insufficient advantages to warrant production and fielding as a standard issue replacement for the Army.

XM40 - Minimum Change, Minimum Risk

The XM40 mask emerged amid the publicity surrounding the Army failure to type classify the XM30. "Type classification" is the term used by the Army to signify that a material or system is deemed ready to change classification from the development stage and proceed into production stage and subsequent fielding. Typically, when a program has an "X" designation such as the XM30, type classification would mark the point where the "X" is dropped from the title. Cancellation of the XM30 prompted a new acquisition strategy for bringing a protective mask into production and fielding. In July of 1982 the Army declared a minimum change / minimum risk (MC/MR) requirement in which no technological challenges would be included in the development of the XM40 series. The goal of this MC/MR strategy was specifically to combine the silicone face blank pioneered earlier on the XM29 project with the established mechanically attached rigid lens system of the current issue M17 mask. The XM40 also retained the replaceable cheek filter canister design of the XM30. The XM40 essentially reverted to the M17 metal clamp design and assembly technology used for the eyepiece due in part to challenges presented by insert molding process. Little design flexibility was afforded the development contractors. In an effort to gain the best mask possible through competition, the Army awarded multiple source contracts to bidders from the U.S. and then extended competition internationally. Meanwhile, by the early 1980's many of the M17 series masks suffered from significant age and usage. The Army elected to reopen the M17 production line in 1983 concurrent with XM40 development. This effort produced the M17A2 mask.

Management Approach

The mask program was structured somewhat similarly to what is presently associated with an Integrated Product Team approach. During the XM40 development program, the Army had what was known as a Configuration Control Board (CCB). The CCB was organized under the US Army Chemical Research Development and Engineering Center at Edgewood Arsenal, Maryland. The CCB incorporated functional areas including: procurement, development, producibility, documentation & specifications, quality assurance, integrated logistics management and maintenance. Functional areas in the Army program were often paired with counterpart personnel from the contractor teams. Contractor and Army managers interviewed for this study indicated that in many instances these functional counterparts interacted on a daily basis throughout the XM30, XM40 and M40 series programs. Program managers reported frequent contact from both Government and contractor sides.

The U.S. Army Armament Munitions and Chemical Command (AMCCOM), parent organization of the Chemical Research, Development and Engineering Center, entered into contracts for XM40 research and development with several firms. The contracts

specified development of a set of specifications called a Technical Data Package, tooling, molds and equipment for the XM40 program. Contracts were awarded for Engineering Development and Design to Scott Aviation, as well as ILC Inc. of Dover, Delaware and Pittsburgh, Pennsylvania based Mine Safety Appliances (MSA) as part of an acquisition strategy based on competition. In addition to the three domestic competitors, a fourth contract was negotiated with Avon Industries, Ltd. of the United Kingdom who submitted a mask design known as the US-10. Avon licensed out production to Ames-Avon located in New Jersey. A 90-day period allocated as Phase I of the XM40 program rapidly ensued. Each bidding company was required to produce its own mask concept, assemble and submit 30 masks to be entered into a Design Qualification Test administered by the Army.

Freshly aware of criticism publicly spread upon the XM29 and XM30 programs, the Army subjected the Phase I mask to a Design Qualification Test that took place at four operational test sites targeted for early user evaluation under ambient conditions. A goal of Phase I was to get early prototype masks into the hands of soldiers. This served to help prevent failure much later in operational testing as the Army experienced previously in the XM29 and XM30 programs. Mask requirements included both respiratory and skin protection for the head and neck area of the soldier. The combination of the silicone face blank conjoined with a hood extending down past the neck area provided the necessary biological and chemical agent penetration protection called for by Army requirements. . Contractors were informed of the results of the Design Qualification Test only after completion of that testing. The Mine Safety Appliance design was the first to be eliminated during Phase I. In October 1983, Phase II of the XM40 program was launched. Remaining contractors were required to submit a proposal for continuing Engineering Development on the XM40. Phase II would last for a period of more than three years terminating with type classification of the M40 mask in May of 1987. At least one contractor expressed concerns with the way the competition-based selection process was administered by the Army. This contractor felt a lack of access to data collected by the Army and limited interaction with the end users hindered their mask design and development. Specifically, the inability to interface directly with users at Developmental Testing and Operational Testing (DTOT) centers was noted. Army program office personnel tended not to agree with this assessment.

Design Chosen

In January 1987 the U.K. based company Ames-Avon was dropped from the XM40 development competition. A Formal Source Selection Process was then implemented to select between the Scott Aviation and ILC mask designs. The Scott Aviation design was subsequently selected as the design for production of the M40 series. ILC had filed a claim with the U.S. General Accounting Office (GAO) in protest due to Army failure to award the contract in accordance with its own formal selection criteria.

Acquisition Strategy

The Army's original mask acquisition strategy called for an overall sixty percent / forty percent sourcing and production plan. In other words, an initial prime contractor should provide sixty percent of the final production of masks. This allowed for the remaining forty- percent to be awarded to separate sources, possibly when better cost, schedule and performance outcomes could be achieved. Advantages of multiple sourcing can be to promote price competition and reduced risk of relying on a single vendor source.

Mine Safety Appliances, which had a long record of design, development and production of masks for the Army, was not permitted to participate in the bidding process for the initial M40 production contract. In accordance with the acquisition strategy for the production contracts, the only companies authorized to bid [on the initial production contract] would be those that made it through the development program. As a consequence of MSA's elimination after the Phase I design and development period, it became ineligible as a possible contractor in the initial contract. This resulted in a lawsuit filed by MSA against the Department of the Army to overturn the this elimination decision. During the ongoing period in which the Formal Source Selection process was taking place, MSA first sought an injunction through the U.S. District court against the Army to prohibit the solicitation for bids on the M40 production contract. From the Army perspective, issuance of such an injunction could effectively delay the M40 program. From the MSA perspective, this was an attempt to overcome the perceived unfairness of this unusual exclusionary bid policy. The injunction was not granted to MSA, however, MSA continued its litigation efforts. Despite this ongoing dispute, the Army issued a formal contract solicitation.

For a period of six months in 1987 the Army was embroiled in U.S. District Court action. The Army case was represented by lawyers appointed by the U.S. Department of Justice and assisted by Army technical personnel consisting of M40 project manager and deputy project manager in addition to the project's contracting officer, Radford Baker. The lawsuit ended on May 1, 1987 after the Army was cleared of all counts charged by MSA.

Following type classification of the M40 protective mask in the month of May 1987, the first award of a production contract was made on June 24, 1987. Scott Aviation was the winner of this award contract specifying delivery of 300,000 M40 ("infantry") and M42 ("tanker") masks. Within two months a Configuration Control Board for the M40 was formed and a configuration control plan was established. Following the contract award Scott Aviation quickly established a new mask production facility in Hebron, Ohio under a very accelerated schedule. It is important to recall that prior development took place in California. The new production facility was established with an almost entirely new workforce. Only a few people from Scott's California based development program made the transfer to Ohio. This may have proved to be an Achilles heel in execution of the production contract. Warren McCormack served as the Scott Aviation Program Manager

during the XM40 development. McCormack apparently did not transfer from California development project to the Ohio facility but did spend a considerable amount of time working to get the Hebron facility started up and running. The Research and Development Centers, such as Edgewood were allowed to retain CCB duties during this time of M-40 initial production until the Technical Data Package could be validated and stabilized.

Stormy Seas

The initial contract award to Scott Aviation, in accordance to the acquisition strategy chosen by the Army, consequently excluded ILC (the only other bidder for this contract). ILC took action by filing a formal protest with the U. S. General Accounting Office (GAO). As a result of the protest, GAO directed the Army shut down the Scott Aviation contract two weeks following the M40 contract award. A period of 90 working days was allowed under the protest for the GAO to come up with a decision over the outcome of the Formal Source Selection Board. The Army formulated and presented a rebuttal to the GAO protest during this time. After the initial two weeks the contract was reactivated, however the Hebron, Ohio production facility was shut down during this period and the protest continued. In November of 1987 the GAO sided with ILC Dover, forcing a re-evaluation of the initial contract award. Even further complicating the situation, Ames-Avon decided to launch an international protest, which directly involved the Army and the U.S. State Department.

As a result of the November 1987 decision handed down by the GAO, a compromise was reached which fundamentally altered the acquisition strategy of the Army mask program. This compromise reached between the Army and the GAO called for **new bidding** of a portion of the initial contract. The effect was a dividing of the original 300,000-unit contract between the three companies, which originally competed under the Phase I development of the XM40 program.

Meanwhile in 1988, the Army proceeded with the training for the initial fielding of M-40 series masks at the U.S. Army Chemical School in Fort McClellan, Alabama. In September of 1988, MSA & ILC Dover were awarded concurrent contracts to satisfy the GAO decision. It is significant to note that MSA and particularly ILC Dover were required under these new contracts to adopt the Technical Data Package and mask design chosen for Scott Aviation after Phase II of the XM40 competition. ILC and MSA (MSA facility located in Esmond, Rhode Island) were confronted by major re-tooling, molding and equipment challenges to adapt to the Scott Aviation design which differed from their own earlier XM40 mask prototype production. The two additional contractors reported difficulties in adapting Technical Data Package under the new contracts and production arrangements which naturally affected the amount of time needed to ramp up production efforts. Insert molding problems encountered by Scott Aviation developers and tooling problems had to be overcome by MSA & ILC in order to satisfy requirements of the

Technical Data Packages. A production process had to be established, as MSA and ILC had a short time for a production process to be in place due to the timing and nature of the litigation in the selection and contract award process. Bringing all the elements together to begin mask production required a major effort and commitment on the part of both firms. Don Cohee, of the ILC mask program, recounted a myriad of issues which included initially grappling with the Scott Aviation Technical Data Package, acquisition of tooling and trying to work through and straighten out errors in molding process as well errors in the Technical Data Package.

Brad Walters, a member of the ILC program office staff characterized the situation this way:

“Basically we received a Technical Data Package that wasn’t ready to go into production, so we spent two and a half years working with the government to get a Technical Data package that was producible...Scott had a data package and had built something [M40] that didn’t necessarily meet the Technical Data Package to its fullest. [Keeping in mind] it met the performance side of it, but not the data side of it. So we spent a lot of time working with the Army to get the data to match the design”.

Indeed, it turned out to be well after the Gulf War before the two additional contractors resolved problems such that full production of the M40 series mask could be reached. Recall again that the urgent need for masks in the Persian Gulf War could not be foreseen or expected during the pre war 1988 –1990 production timeline.

M40 Production: Problems...

During this turbulent time of litigation and contract renegotiations, Scott Aviation experienced ongoing production problems, on time delivery failures and disputes with the government over differences in the Technical Data Package. As recorded in legal appeals, Scott Aviation asserted that performance was adversely affected because of “government inspectors operating with a different Technical Data Package than that set forth in the contract, and problems with the government furnishing tooling, molds and equipment.” It was strongly disputed who was at fault for these problems.

In the period of May through August of 1989, the contracting officer issued numerous partial terminations of the Scott Aviation contract citing default “for failure to make timely delivery” of more than 12,000 M40 masks to be produced under the contract. Tensions between the contractor and the Government ran very high. By October of 1989 Scott Aviation wrote the contracting officer, stating that “Scott’s ability to continue performance is seriously threatened”. Future delivery schedules “cannot be provided by Scott until all technical issues which are the responsibility of the Government are resolved”.

The problems identified by Scott included:

- (1) Alleged failure of the Government to provide outlet valve discs as Government Furnished Equipment, which disks are necessary to continue production.
- (2) State of the Government Furnished tooling allegedly unsuitable for use in performing the contract – in particular the tooling used to produce 'nosecups'.

The contracting officer expressed 'serious concerns' at this time about Scott Aviation's intentions and ability to produce masks according to the contract. The contracting officer made an offer to pay Scott "up to \$250, 000 to rework or replace Government furnished tooling that Scott had identified as not producing acceptable parts".

Crisis Management

Noted in the challenge by Scott, inadequate government furnished tooling caused the contractors inability to produce small and medium sized nosecups within required specifications. These nosecups were cited as essential parts needed to proceed with M40 mask production. The following month, November 1989, the contracting officer was informed by the president of Scott Aviation that a planned temporary shutdown in December 1989 was to take place due lack of available small and medium sized nosecups.

The president of Scott Aviation followed up with communication to the effect that Scott was being forced to halt production and lay off the Hebron, Ohio work force – due to the unresolved technical problems. The Government contracting officer responded by setting a new delivery schedule for the contract, beginning at the end of January 1990.

Scott Aviation cited this "unilateral modification and delivery schedule requiring Scott to deliver the Outlet Valve Disc [known to be unacceptable for the M42 tanker mask] as a material breach of contract by the Army".

On December 4, 1989, Scott Aviation officials and the Acting Assistant Secretary of the Army held a meeting to determine how to proceed with the Scott production contract. Negotiations continued throughout December, and by January 1990 Scott Aviation contacted the contracting officer explaining that the Hebron facility would temporarily be used to assemble another mask manufactured by Scott to reduce costs and employ some laid-off production workers. Scott maintained that it was "willing and able to resume

production on this contract once the Army" solved the technical problems associated with the accused material breaches.

Army command concluded that, following the five months delay, settlement was not possible and on January 19, 1990 the Scott production contract was terminated for default for "anticipatory repudiation of the contract".

Findings

In April 1990 Scott filed an appeal of the termination for default with the Armed Services Board of Contract Appeals (ASBCA). The ASBCA upheld the appeal of Scott Aviation in July of 1990, just one-month preceding the invasion of Iraqi forces into Kuwait. Principally the ruling was because the Army failed to follow the terms of the contract which specified that a written cure notice must be sent specifying the failure that must be rectified and allowing the contractor a minimum of 10 days to cure the problem. Due to this oversight, the termination for default was converted to a termination of convenience for the Government.

Scott Aviation's successful appeal resulted in termination of the M40/42 mask production contract for convenience and was followed by the federal Board of Contract Appeals (under the Controller General) ruling in April 1991 causing the Government (and therefore the taxpayers of the U.S.) to pay for all termination costs. Those costs involved shutting down the Scott production facility. In hindsight, it appears that a great deal of taxpayer money was spent in termination of a contract due to inadequate execution of the production contract and possibly ineffective management of the Technical Data Package. This may have stemmed from the fact that the Army simultaneously managed three slightly differing versions of the Technical Data Package in three separate contracts, with three separate contractors.

Under the circumstances, contractors reported a significant frustration level of management within the Army Mask Management Office. One contractor found it particularly frustrating when they attempted to point out problems with the Technical Data Package. Regarding the difficulties during the period between 1988 and 1991, some contractors interviewed for this case expressed the opinion that the Army was slow to recognize that the process of pointing out and correcting flaws in the Technical Data Package was in the best interest of the Army. Faster correction would have enabled production to proceed relatively quickly once these issues were taken care of, thereby avoiding future costs and delay during full production. Army technical personnel cited the perceived slowness as the time it took to push these issues through the Configuration and Control board.

An example illustrating this involved a complicated series of water line drawings that defined the inside of the faceblank – which is a highly complex three-dimensional shape

to fit a range of soldiers' faces. The data that tied together this series of drawings did not provide an optimal solution to enable successful production. A contractor expressed that some pressure was exerted from the Army to simply proceed and that it took time to convince Army management of the magnitude (and urgent need) to fix this type of problem as well as other problems not listed here. However, it is reasonably clear that once the Army became fully aware and understood the problem they moved successfully to overcome such obstacles. On the whole, the Army did in fact work successfully with the contractors involved. The M-40 mask series did ultimately reach full production as a result.

Authors Notes:

Designing, developing, testing and producing a significantly improved, reliable, effective, comfortable and user friendly protective mask for a multitude of hazardous and lethal combat environments is, everyone agrees, a complicated and difficult process. Complex coordination, engineering, trial and error and technology management all played a part over the course of many years to yield the M-40 series. By all accounts the M-40 series, while not perfect and not without very significant time, delay and frustration - turned out to be an excellent mask system due to the persistence of many individuals and teams within the Army and each of the contracting companies involved.

A limited number of M-40 Series masks were fielded during the course of the 1990 Persian Gulf War. This resulted from an operational need to provide protection to some personnel who experienced fit difficulties with the standard issue protective masks. Approximately 500 masks produced by the Scott Aviation facility were shipped to the theater of operations in the Persian Gulf and issued to personnel having special fitting needs. Anecdotal feedback indicates that these low production M-40 series masks were able to meet operational needs and had no significant problems associated with their fielding or performance.

Post Gulf War Production

Material Release and Delivery

The M-40 series masks were granted Material Release by the U.S. Army in 1991. First shipment of masks was made at U.S. Army chemical storage facilities on Johnston Atoll, delivered to surety personnel in November 1991.

Contract Issues

The Army awarded ILC and MSA additional monies in 1992 following a request for equitable adjustment. Both ILC and MSA incurred significant costs based on the fact that it was "assumed [we] were going to receive an acceptable Technical Data Package and be able to [move forward with the contract] on day one". Money was awarded because both ILC and MSA were unable to proceed initially due to Technical Data Package errors and other problems that caused delay and added costs. Brad Walters, of ILC, described a period between 1988 and early 1991 in which ILC grappled with a mask system composed of 150- 200 drawings for which on the order of 600 changes (Notices of Revision) were instituted. Understandably, this large volume of change caused difficulties, logistical challenges and delay on both the contractor and government side. At this stage, Scott Aviation had exited M40 production. The contractors hired some former Scott Aviation employees in order to assist in their understanding and ability to resolve issues needed to make the mask producible according to the design drawing package.

Change in Production

MSA successfully persuaded the Army mask community to accept polycarbonate lenses to replace glass lens for ballistic protection. Both MSA and ILC were required to perform a significant one-time retooling effort to get assembly equipment to accept polycarbonate lens. This was due to its differing design and configuration of the polycarbonate lens needed to sustain required optical quality.

Full Production and Fielding

When the issues of the Technical Data Package were worked out, the CCB and production responsibility moved over to Rock Island Arsenal, Illinois under the Readiness Component of AMCCOM. Interviewees indicated that full production of the M-40 was reached during 1992, approximately two years after the Gulf War conflict. Army and contractors interviewed indicated that production proceeded relatively

smoothly from 1992. In 1992, the M40A1 was developed with a "Quick-DoFF Hood" and improved nose cup design that increased user comfort and speed of use. In 1988, the cost of an M-40 mask was about \$150. By the end of the 1990s cost reduction efforts dropped the cost to less than \$100 per mask. The M40 successfully replaced the M17 mask as the main protective mask of the Army infantry. In general, the masks have received favorable acceptance. According to the Chemical Biological Defense command, assessments with the new M40's in the early to mid 1990's revealed a lack of preventative maintenance checks and services but has since been addressed. By 2000, more than 1,500, 000 masks had been produced. The M-40 series also gained use by the U.S. Marine Corps as well as chemical surety units and demilitarization workers.

I

M829A1

ANTITANK ROUND

120 MM Cartridge (M829A1)

“Silver Bullet”

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120 MM Cartridge (M829A1)

“Silver Bullet”

Introduction

In 1985, the Armament Enhancement Initiative (AEI) was implemented to develop new ammunition for the U.S. Army Abrams tank to counter the growing threat from advanced Soviet Union tanks, such as the T64, T72, T72M1, T80 and the postulated Future Soviet Tank. The AEI Acquisition Strategy signed in January 1985 by Dr. Jay R. Sculley, Assistant Secretary of the Army for Research, Development and Acquisition states: “Project Manager, Tank Main Armament Systems (PM TMAS), Picatinny Arsenal, NJ is responsible for the management of specific efforts.....to include personnel resources, procurement actions, legal actions, quality assurance, facilitization and other technical and programmatic activities.” The lead technical support for the program (in both development and production) was provided by the U.S. Army Armament Research, Development and Engineering Center (ARDEC), also located at Picatinny Arsenal, NJ. ARDEC provided engineering expertise in the development/integration of the complete round, which included several key components such as the projectile (sabot and penetrator), cartridge case and propulsion system with cool primer. Working closely with ARDEC was the Army Ballistic Research Laboratory (BRL) at Aberdeen Proving Ground, MD, (presently part of the Army Research Laboratory) which contributed to the designs of the depleted uranium (DU) penetrator and propellant, and the Honeywell Corporation, who was selected as system contractor in the development of a new 120 mm tank round. This round, designated M829A1, was later nicknamed “Silver Bullet” by U.S. armored forces during the Gulf War.

At the Army briefing that introduced the possibility of developing and fielding a longer, thinner, more effective tank-fired projectile to the Army leadership, the Project Manager said that the team could develop a new penetrator, sabot and propulsion system and still field the bullet in two years rather than the typically much greater time required to go from research to production. They did it in three. There were, however, certain circumstances that made this possible.

Background

In the early 1980's, military intelligence projected that the Soviet Union would have a new tank in the field within five years that could not be defeated by the current armament system on the Abrams tank. The Abrams was the most advanced tank the United States and several of its key allies possessed. Intelligence analysts believed that the Soviets planned to deploy a new type of passive armor on their tanks and then add an explosive reactive armor appliqué (an outer layer) to ensure their tanks could not be defeated by the Abrams main gun ammunition.

This anticipated change to the threat led to the Army's initiation of an Armament Enhancement Initiative (AEI). This Initiative provided funding over a number of years to develop several different types of (enhanced) ammunition for the Abrams tank. Tankers customarily refer to kinetic energy ammunition (wherein a heavy rod penetrator strikes the target tank at very high velocity) as "sabot" to distinguish it from a different type of ammunition that detonates and explodes; they call the latter "Heat" (High Explosive Anti-Tank). The Abrams tank carries and fires both "sabot" and "Heat" ammunition.

As part of the AEI program, the Army planned to develop several new "sabot" rounds, as well as a "multi-purpose Heat" round containing a high explosive that detonated and projected a high speed metal jet and fragments through an enemy tank, a 105mm/120mm "Staff" round that could explode over the top of an enemy tank and send a high speed metal slug down through the top, and a rocket-propelled accelerating projectile that carried a kinetic energy penetrator. In the end, the "sabot" and "multi-purpose Heat" rounds were successfully fielded as a result of the AEI program, with other technologies developed carried forward into future munition efforts.

The M829E1 was the designation given to the first "sabot" round developed for the 120mm gun on the Abrams as part of the AEI program. This round was followed by a second sabot round, called the M829E2, but this second round was not fielded until after Desert Storm. The goal of the M829E1 development project was to develop a bullet that could penetrate the armor on Soviet Union tanks that were expected to be fielded in the next five years and get the new ammunition developed and into the field in about two years.

At the time of interest in this study, the Army Ballistic Research Laboratory had responsibility for, among other things, developing and demonstrating new technologies for improved tank ammunition. In other words, the Ballistic Research Laboratory performed research on interior, exterior and terminal ballistics (referring to phenomena that occur within the gun tube, during flight, and while interacting with the target, respectively) and then capitalized on the new knowledge they produced by designing and demonstrating prototype components and subsystems .

Due to the intelligence reports concerning the projected Soviet tank armor, researchers at the Ballistic Research Laboratory set out to develop a penetrator that had both high density and high ductility. In so doing, they were trying to develop a penetrator that had the ability to bend and flex without breaking during the armor penetration process.

The longest U.S. penetrator that had been fielded at that time was the 450mm long penetrator in the 120mm M829 cartridge. One of the approaches taken by the Ballistic Research Laboratory was to see if a longer, thinner depleted uranium penetrator could provide even better penetration. Many experts believed that a longer, thinner penetrator would not work because it would break on launch, or shortly thereafter.

Just prior to the start of the Armament Enhancement Initiative, the Ballistic Research Laboratory had developed and demonstrated a family of four penetrators that had different lengths and diameters. These penetrators were launched from a variety of laboratory guns into range targets representing state-of-art Soviet armor and the postulated future threat. These tests showed that a longer, thinner penetrator could successfully be launched from a gun and also soundly defeat Soviet armor.

The results from these tests were combined with tradeoff analysis, forming the basis for a 105mm kinetic energy bullet technology demonstration program that the BRL nicknamed "Honey Bee." The Honey Bee technology demonstration program integrated a 680mm long depleted uranium penetrator, a lightweight aluminum sabot and a solid-propellant propulsion system. The results from the "Honey Bee" technology demonstration program were so successful that the Army made a decision to cancel the existing 105mm XM900 sabot round development project and redirect the funding to a new 105mm XM900E1 cartridge based upon a longer, thinner penetrator. This penetrator design approach also formed the basis for the 120mm M892E1 and M829E2 development efforts undertaken as part of the AEI program.

Three critical component technologies had to be developed, integrated and demonstrated for Honey Bee to be successful:

1. Kinetic energy penetrator
2. Sabot
3. Propulsion system

Other components, such as the fins, windshield and cartridge case were also required, but they will not be discussed here.

The penetrator material had to be dense and flexible. The research team investigated several different materials before settling on depleted uranium. There are three types of uranium: U238, U234, and U235. Both U234 and U235 are fissionable materials and are used in bombs. When U234 and U235 are removed, U238 is left; however, U238 is still highly radioactive with a half-life of 4.2 billion years.

The research team discovered that the ideal length of a penetrator made of depleted uranium was 680mm for the Honey Bee application. A penetrator of that size weighs 4000 grams, or about 10 pounds, and is extremely dense. While a depleted uranium penetrator 680mm long seemed to be an ideal length for armor penetration, it required a cartridge that was so long it created propulsion problems.

Integrating a very long penetrator into the kinetic energy round meant that the propellant required ignition at the very base of the cartridge. This potentially could lead to unstable pressure waves during the ignition and flame spreading processes, causing the gun to blow up. This meant that the research team would need to develop a new propulsion system that could ignite and burn in such a way as to not create pressure waves.

The most important part of the parasitic hardware is the sabot. The sabot is located on the inside of the cartridge and holds the projectile in place within the cartridge. Along with centering the penetrator in the middle of the cartridge, the sabot also supports the penetrator during launch and keeps it from bending and/or breaking.

The sabot had to be strong enough to support the 4000 gram penetrator and center it in the cartridge, yet light enough to not add excess weight to the bullet and thereby reduce its muzzle velocity. The researchers finally decided on aluminum for the sabot because of its light weight and strength and their extensive experience using it in previous designs.

When fired, the propulsion pellets inside the cartridge ignite and propel the projectile and the sabot to the end of the barrel where the sabot falls away. The depleted uranium penetrator, due to its density and flexibility, penetrates the armor on the outside of the enemy tank and enters the crew/ammunition compartment of the tank itself. The projectile creates spall as it penetrates the enemy tank. Spall is essentially a cloud of high speed armor debris created during the penetration process. Spall and residual penetrator pieces enter the tank crew/ammunition compartment if the penetrator perforates the tank, igniting the ammunition stored in the tank and blowing up the tank from the inside.

At the same time this development and demonstration of a new projectile for the 105mm gun was ongoing, the Army was also developing and fielding a new 120mm gun for the Abrams. This 120mm gun was based on an existing German design. The existence of this gun, coupled with the success of the 105mm Honey Bee technology demonstration program provided a solid technical basis for starting the 120mm M829E1 development effort as part of the Armament Enhancement Initiative.

120mm ammunition is generally more effective than 105mm ammunition because it provides enhanced killing power at longer range. A depleted uranium bullet fired from a 120mm gun leaves the muzzle at about 5000 feet per second, covers a mile in about a second, and strikes a target at slightly less than 5000 feet per second. Estimates show that a projectile fired from the 120mm gun could penetrate about 100mm (four inches) deeper than a projectile fired from a 105mm gun. Beginning with the availability of the predecessor M829 round, the U.S. Army swapped out Abrams tanks with 105mm guns for ones that had 120mm guns to enhance its ability to defeat advanced armor threats such as the Soviet T72M1 tanks. This was particularly important because Iraqi Republican Guard Divisions were equipped with these tanks during Desert storm.

Planning

The planning stage for the Silver Bullet was somewhat unusual when compared to the normal approach for military projects. The Silver Bullet never had to go through the typical steps in order to receive funding. In the early 1980's, intelligence indicated that the Soviet Union was developing a new type of armor for their tanks that could not be penetrated by the 105mm M833 or 120mm M829 rounds being used at the time by the Abrams tank. The Soviets were expected to have the armor fielded within five years.

As a result, a development program was funded under the Armament Enhancement Initiative to develop a new improved 120mm "sabot" round for the Abrams tank. Under the development program, different ideas were developed, tested and evaluated. The concept for the innovative design of the depleted uranium penetrator came about as a result of a series of experiments performed by the Ballistic Research Laboratory. When the tests with a longer and thinner penetrator showed that it offered a viable configuration for a bullet, the BRL made a presentation to senior Army leaders showing the effectiveness of the novel 680mm long penetrator. These leaders believed that the new approach offered a solution to their problem and authorized the funding and development of the bullet based on this new penetrator.

Development

As previously noted, the successful development and fielding of the Silver Bullet was dependent on the development of three critical component technologies. The first technology necessary was the development of a penetrator. The penetrator had to be dense and flexible in order to penetrate the armor of an enemy Soviet tank. The projectile that was finally chosen was a rod of depleted uranium 680mm long weighing 4000 grams.

The second critical technology was the sabot that surrounded and supported the penetrator during launch. The sabot centers the projectile by holding it in place inside the cartridge. It has to be strong enough to hold the projectile in place while being light enough not to add much weight to the cartridge itself. The third critical technology was the propulsion system. The length of the penetrator, and the resulting length of the cartridge, caused a problem when fired from a 105mm or 120mm gun. The penetrator in the 120mm M829 projectile originally fielded for the Abrams was 450mm long while the penetrator in the Silver Bullet was 680mm. While this additional length had shown itself superior in tests against range targets, the added length of the penetrator meant that the propellant would ignite farther back in the cartridge, risking the creation of pressure waves that could blow up the gun.

The design called for the propulsion pellets to burn in a pre-programmed way as the projectile traveled down the length of the barrel. When the projectile left the gun, the sabot was discarded and the only parts of the bullet that would actually strike the target were the penetrator, fins and windshield. In order to penetrate the projected Soviet armor, the penetrator would need to be traveling at about 5000 feet per second.

The Program Manager assigned to the development project concluded that the development project should be sole sourced to Honeywell because they had the demonstrated capability (they were the only contractor with 120mm system experience) to handle the follow-on high rate production. All three of these technologies, so critical to the success of the round, were relatively new to Honeywell. The design of a sabot was not new to them; however, designing one to hold a 680mm penetrator was. One thing that was instrumental to the success of the project was the involvement of the both BRL and ARDEC in support of the Project Manager and his system contractor. The BRL contributed to the maturity of the key technologies at the start of the system project

planning stage. Both ARDEC and BRL further contributed to the readiness of the project at the beginning of the Development phase and remained heavily involved during the contract development effort, while ARDEC primarily contributed to the preparation for the transition from development to production.

Staffing and Location

The project to develop the Silver Bullet never slowed down once it started. It did, however, go through transition. The development team was cross-functional and was set up informally, with the team asking the various organizations in BRL and ARDEC for help as needed. All key skills were represented on the design team.

Most of the people involved with the design team during the development stage had worked with each other before. The members of the team from Honeywell were collocated in the same building while the members of the team from the Army were similarly collocated in one building at Aberdeen Proving Ground, MD. The development and testing carried out by Honeywell occurred at the facility they leased at China Lake, CA.

Validation Activities

No failure modes and effects analysis was done on the system. The individual components of the Silver Bullet were tested separately by the Ballistic Research Laboratory, Armament Research Development and Engineering Center, Honeywell, and the various suppliers involved with the project. Simulations were also run to show that the individual components worked individually.

In addition, the components were tested in a controlled range setting to show that they worked together. These tests were performed by the Ballistic Research Laboratory, Armament Research Development and Engineering Center, Honeywell, and various suppliers. Furthermore, the government agencies, the prime contractor and the suppliers all ran simulations on the system as a whole.

Most of the testing of the integrated components was accomplished using a test stand gun. Project participants estimated that eighty percent of these integrated tests in a realistic environments were carried out using a test cannon mounted on a stand ("test stand") while twenty percent were done using an actual tank.

When viewing the time spent on testing and simulations, sixty percent was spent testing and simulating the individual components of the system to make sure they worked individually. Another ten percent was spent to make sure that the integrated components worked in a realistic setting. The remaining thirty percent of testing and simulation time was spent on all other validation purposes.

The project team and the testing community worked well together. Significant attention was paid to the need to achieve quality test and simulation results and project participants believed the components and the system were validated at the right times in the program.

Participants and Communications During Development

The team leader on the project did not have a problem getting resources whenever necessary for the project. He had both design and production experience and was highly competent from a technical standpoint.

Team members represented virtually all skills need to successfully develop and produce the Silver Bullet. There was very little turnover because the Research and Development contract had a production option in it for at least two years. The team came to know exactly where to go when it needed help.

The project was a priority with Honeywell's management. As a result, management project reviews were constructive and helpful. Final reviews were conducted at key decision points. One advantage was that the team never faced any uncertainty as to the future of funding for the project.

In addition to the regular members of the design team, upper management from Honeywell regularly attended formal reviews. Senior military officers were also present at these formal reviews. The upper echelons of management showed support for the project on numerous occasions.

Planning meeting including both design and production people were held many times. At these meetings, physical prototypes were passed around and test articles and/or pre-production parts were discussed and examined jointly.

Problem Solving

All things considered, the development project moved from Planning through Development to Production with relatively little difficulty. There was adequate funding for this effort and there were no cut-backs in project resources or changes in strategy that could hamper efforts. The ideas and approaches employed in the project were readily accepted by the Ballistic Research Laboratory, Armament Research Development and Engineering Center and the Program Office. Everyone was working together to reach a common goal.

There was a problem with the fin that was uncovered late in the development process that required a major effort to correct. The technology was difficult to scale up from the lab and pilot tests to full production. Testing and quality control took longer than planned on the project.

Project Outcomes

The Silver Bullet was approved for production and fielding, and put into full production as the M829A1. Production started prior to Desert Storm. After acceptance, there were only minor changes to the design. The M829A1 was deployed prior to Desert Storm and greatly exceeded the user's expectations to the extent that it was the soldiers in the field that nicknamed the M829A1 depleted uranium projectile the "Silver Bullet." During Desert Storm Abrams tank crews quickly learned that the M829A1 provided them

capability to engage and destroy T72M1 and other Iraqi tanks with a single shot at ranges up to 3.5 km, beyond the effective range of Iraqi tank fire. The Iraqi tanks thus became "sitting ducks" that could easily be "picked off" by Abrams tank crews firing the M829A1.

J
MULTIPLE LAUNCH
ROCKET SYSTEM

Multiple Launch Rocket System

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Multiple Launch Rocket System¹

During World War II both the United States and the Soviet Union fielded early versions of a multiple launch rocket system. During the Korean War the US continued to use modified World War II multiple launch rockets known as the M91. Following the Korean War through the late 1960's there was a general lack of interest in the US in the further development of this type of weapon system. During this timeframe the Soviets continued to develop their MLR systems known as the Katyusha. In addition, throughout the 1960's West Germany, Japan, and Israel fielded versions of this weapon. While the reasons varied for the deployment of MLR's in these countries, it is interesting to note that officers in the West German and Japanese armies had experienced the effects of being on the receiving end of the Soviet Katyusha during World War II. The Israelis had significant experience with the Soviet versions of this weapon being used against them by Egypt and Syria in the 1956 and the 1967 Arab-Israeli wars.

By the mid to late 1960's the Soviet buildup in Eastern Europe was reaching staggering proportions and NATO forces were significantly outnumbered. During this timeframe battle simulations were conducted by the Field Artillery Center known as the "Red Leg" studies. These simulations demonstrated, that under multiple scenarios, NATO artillery would be overwhelmed during surge periods of attack by the sheer number of enemy targets. In non-nuclear scenarios an imbalance was clearly developing which favored the Warsaw Pact.

Lesson 1: The Role of the Laboratories in the Early Stages of Development

During this period in the mid 1960's the Advanced Systems Concept Office of the Army Missile Command began concept development and coordinated work on the beginnings of a multiple launch rocket. Herman Oswell of the Advanced Systems Concept Office developed a concept for what was labeled the Highly Accurate Rocket System (HARS). The basic concept was to design a rocket system that would be as accurate as artillery with the advantage of rapid area saturation fire. At the time the state of the art in technology would not permit the production of this weapon. So Oswell, with the collaboration of engineers in MICOM labs such as Propulsion, Structures, and others, set out to advance the technology so that an MLR could be designed and built. What emerged from this effort was the Multiple Artillery Rocket System (MARS).

In order to increase the accuracy of MARS each rocket was to have a directional guidance system, but this would significantly affect cost. Another feature was propulsion zoning so that range could be quickly altered. However, this proved to be a very difficult technical problem. By 1968 the lab was ready to obtain contractor support for the project in order to attempt to solve the technical problems. In January 1969 five defense contractors received contracts to conduct preliminary work on MARS. These companies included Martin-Marietta, Northrup, Chrysler, Boeing, and Vought. Based on the results of the contractor reports and a cost and operational effectiveness analysis the Army cancelled the program in March 1970.

While this event was a significant setback, Herman Oswell and his colleagues with the Advanced Systems Concept Office and MICOM laboratories set out to develop a concept for a more cost effective multiple launch rocket system. To improve cost effectiveness they made the decision to design free flight rockets that were as accurate as possible without the aid of costly guidance systems. The resulting system would be less accurate than conventional artillery. However, it would have the advantage of rapid firing and the ability to saturate an area destroying light vehicles, equipment, and infantry. During the early 1970's Oswell began to seek support from the Field Artillery for the modified multiple launch rocket concept that he and his associates had been developing in the lab. This persistence on the part of engineers in the laboratory proved to be very important for the future engineering development and funding support for the system.

Lesson 2: Developing and Sustaining a Broad Base of Funding Support

During the early 1970's Oswell began to make allies within the Field Artillery. This apparently was not always an easy task. According to Oswell the Field Artillery at the time had come to accept missiles like the Pershing or the Lance for special applications. However, many officers viewed free flight rockets as simply a replacement for canon artillery. In any case, it became increasingly apparent to many in the Field Artillery that some form of MRL was necessary to augment traditional artillery during battle scenarios in which NATO forces were significantly outnumbered.

During this same timeframe support began to develop within the Pentagon as well. David Hardison, Deputy Undersecretary of the Army for Operations Research, became convinced that an MRL with a design approaching what Oswell and his associates were proposing would have the efficacy that was needed to augment current forces in Europe. Hardison became an advocate for the system and began to convince other Pentagon decision makers of the potential cost effectiveness of this system.

General Walter Kerwin, the Army Chief of Staff, and General William Depuy, the commanding general of the Training and Doctrine Command (TRADOC) were initially skeptical of the MRL. However, by 1975 they were convinced of the potential of this system primarily from the perspective of Hardison's arguments of manpower savings and cost effectiveness. This series of events illustrated the importance of obtaining the support of a high level decision maker, who then convinces other key decision makers of the merits of the program.

Lesson 3: Effective Project Planning

By September of 1975 the Department of the Army approved a letter of agreement for a General Support Rocket System (GSRS) that would be a multiple launch rocket. A special study group was created to define the GSRS characteristics and to conduct a concept definition study that included a cost and operational effectiveness analysis. At Army Missile Command in March of 1976 the Advanced Systems Concepts Office announced the award of five concept definition study contracts. The concept definition phase contracts were awarded to Boeing, Northrup, Martin-Marietta, Emerson Electric, and Vought. Each contractor was tasked with performing a four month study and to outline technological approaches for the multiple launch rocket system. This included both life cycle and program cost estimates.

Based on these studies, a system concept was generated. The multiple launch rocket system would consist of a self propelled launcher loader (SPLL), two disposable pods (each containing six rockets), a fire control system, and an azimuth and position determining system. The rockets would be loaded in the launch pods at the factory, shipped and stored in the pods, and fired from the pods. The disposable launch pods would enable the system to meet operational and logistical manpower limitations, as well as provide a rapid reloading capability. The fuze settings would be accomplished automatically by the fire control system. The carrier itself would be a derivative of the Infantry Fighting Vehicle and would use the same engine, transmission, and other mechanical systems. The cab would contain space for the three man crew. The GSRS was to be designed to include a submunition warhead. The submunition warhead would provide the capability to attack the enemy's indirect fire weapons, air defense systems, and light material and personnel targets. Later, a scatter-mine warhead would be added to provide the capability to delay, impede, and assist in the destruction of the enemy's armored forces, especially at ranges beyond the delivery capabilities of artillery. A third warhead that would be added later was an anti-armor terminal guided warhead.

In July of 1976 the GSRS (later to be renamed MLRS in 1979) project office was established. Colonel Kenneth Heitzke was named project manager. Heitzke immediately named Lawrence Seggel, an exceptionally talented engineering manager, as the Deputy Project Manager. Seggel had worked in the Advanced Systems Concept Office and thus had extensive knowledge of MARS and what would be required to successfully develop and produce a multiple launch rocket. The importance of this staffing decision cannot be minimized. It was not only important because Seggel was a talented engineer and manager, but his past background in ASCO facilitated the technology transfer based on the previous experience from the laboratories.

There was a clear division of labor between Heitzke and Seggel. Heitzke spent most of his time building and maintaining support for the program among the various constituencies within the Army, the Department of Defense, and Congress. Heitzke also began work on establishing partnerships with NATO allies for a joint effort in the production of a multiple launch rocket system. Seggel was given considerable autonomy to staff the project office and to begin initial work. He was responsible for developing and executing what turned out to be a highly successful acquisition strategy. Heitzke understood that Seggel possessed the experience and expertise to manage the project and therefore the delegation of decision making was complete and effective.

In December 1976 the Army Systems Acquisition Review Council I (ASARC) determined that the project was ready to enter the validation phase. At a second ASARC meeting in April 1977 a program alternative was approved in response to the need to accelerate the program schedule. This alternative provided for validation (advanced engineering development) and early production if the development risks were satisfactorily reduced during the validation phase. Competition for the validation phase was initiated with requests for proposals issued to 31 companies. In September 1977 two contractors, Vought and Boeing, were selected for the prototype development effort. Boeing was teamed with Thiokol Corporation for the solid propellant propulsion system and with Teledyne Brown for the fire control unit. Vought was teamed with Atlantic Research Corporation for the propulsion system and with Norden for the fire control unit. In particular, Vought had developed a high degree of internal expertise on free rockets

during the early 1970's. This base of experience would prove to be extremely beneficial as the program evolved. FMC was awarded the contract for development of the carrier for the Self Propelled Launcher Loader. This was to be a modification of the Army's Infantry Fighting Vehicle.

During the Validation Phase Vought and Boeing were tasked with systems development and integration responsibilities that included design, fabrication, testing of hardware, and development of supporting documentation. Each firm was given 29 months to design and produce the prototypes for competitive evaluation. The government assumed responsibility for providing the XM445 fuze, the MLRS carrier, and the M42 submunitions. Vought, Boeing, and the Army Operational Test and Evaluation Agency (OTEA) conducted developmental and operational tests on the MLRS hardware design and determined the potential for the designs to satisfy system requirements in a cost effective manner. Furthermore, development tests beginning in November 1977 and operational tests beginning in December 1979 demonstrated that technical risks had been minimized. The validation phase schedule is presented in Figure 1.

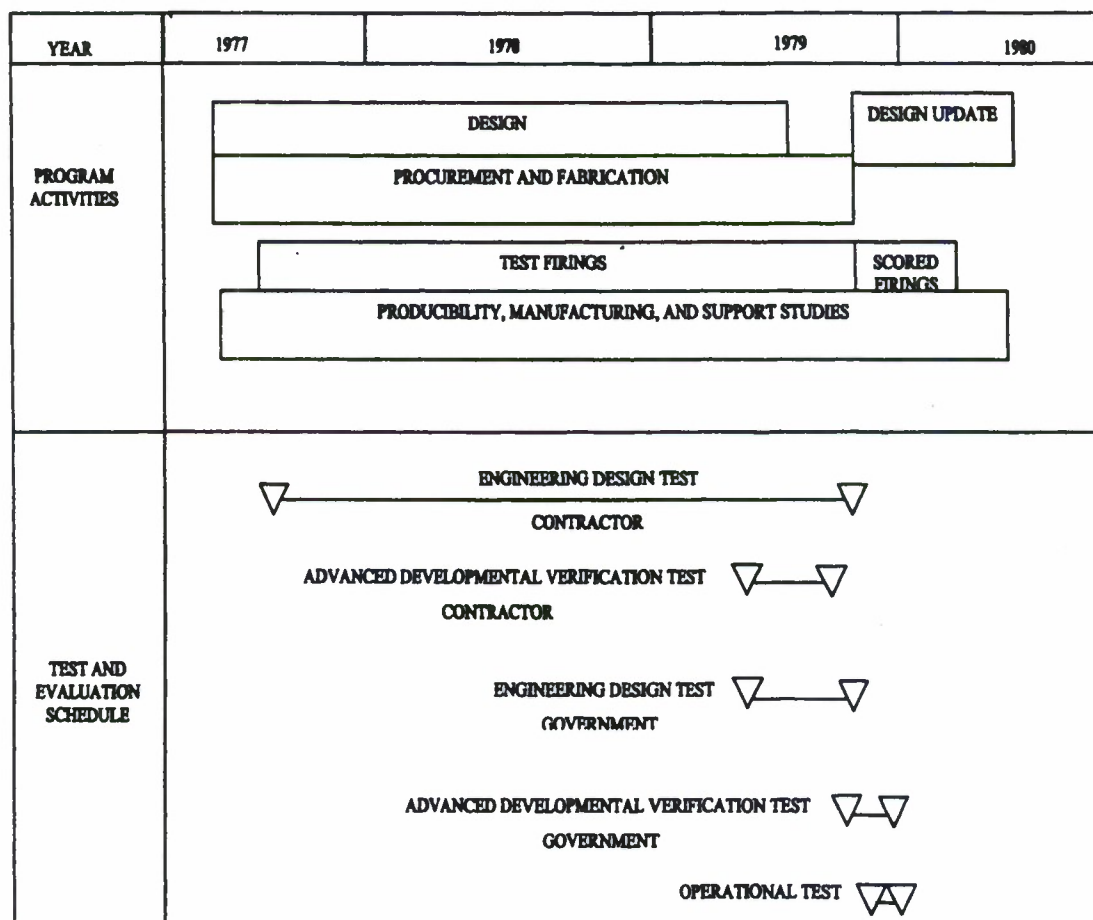


Figure 1 – Validation phase schedule

Each of the contractors fabricated and tested three prototype launcher systems with flight test equipment and hardware. Upon completion of the contractor and government development tests and the operational tests, the project plan included four options. The first option was if the MLRS system were proven to be sufficiently mature by the end of the validation phase the program would enter the maturation/production phase. The contractor for that phase would be selected from the two competing validation phase contractors through the source selection evaluation process. The second option was if the validation phase testing demonstrated that the hardware and system design were not sufficiently mature to enter the production phase, this option would provide for the entry into the full scale engineering development phase with both contractors. The third option assumed the same schedule as the second option except that a single contractor would be selected from the two validation phase contractors by the source selection evaluation process for entry into full scale engineering development. The fourth option would be the cancellation of the MLRS project if it did not demonstrate potential to satisfy the operational requirement. Following the validation phase the hardware was proven to be sufficiently mature to justify the adoption of the first option.

Following the validation phase in November 1979 Vought and Boeing submitted proposals for the maturation/initial production phase contract. In April 1980 the ASARC met and determined that one contractor should be selected to proceed into the maturation/initial production phase. Prior to this there had been consideration of issuing two contracts for MLRS production. However, this was determined to be a less cost effective approach. Vought was awarded the contract for \$115.8 million for maturation, low rate production, and initial production facilities.

The schedule for the maturation/initial production phase is presented in Figure 2. Tasks included completion of the full scale production technical data package, incorporating final design to unit cost tradeoffs, the correction of validation phase performance deficiencies, complete production engineering planning, finalizing firing algorithms, developing training aids, developing automatic test equipment, finalizing the maintenance package, and integrating warheads.

The low rate production contract required Vought to deliver 12 launchers and 1374 rockets by January 1982. These items were to be used for training crews and mechanics, and for testing. During 1980 and 1981 the MLRS project office exercised its option to increase the number of systems produced during low rate production for additional testing. In August 1982, Vought delivered the first production unit and this was soon followed by the delivery of 28 others. By March 1983 the first MLRS unit consisting of a battery of nine SPLs was formed at Fort Riley, Kansas. The second battery was formed in Germany in March 1983. Subsequently, units were fielded at a rate of three per month as Vought moved into full scale production in 1983.

Lesson 4: Achieving Effective Cost Control

Seggel's strategy was to take a technologically conservative approach, to set realistic objectives and then exceed them, and most importantly, to design to cost. Seggel understood that MARS had been cancelled because of a failure to design to cost and because unrealistic expectations for the program had been created. An intensive design to unit production cost (DTUPC) program was established early on in the project. As a

result, the project was characterized throughout early development by multiple trade-off decisions that were based on cost and operational effectiveness analyses (COEA). The early COEAs aided in establishing broad system requirements and design objectives. During development specific contractual design to unit production cost goals were set for the rocket, the launch pod/container, and the launcher loader. Extensive design trade-off analyses were performed by both the MLRS project office and the two contractors using Life Cycle Cost (LCC) as the measure of effectiveness.

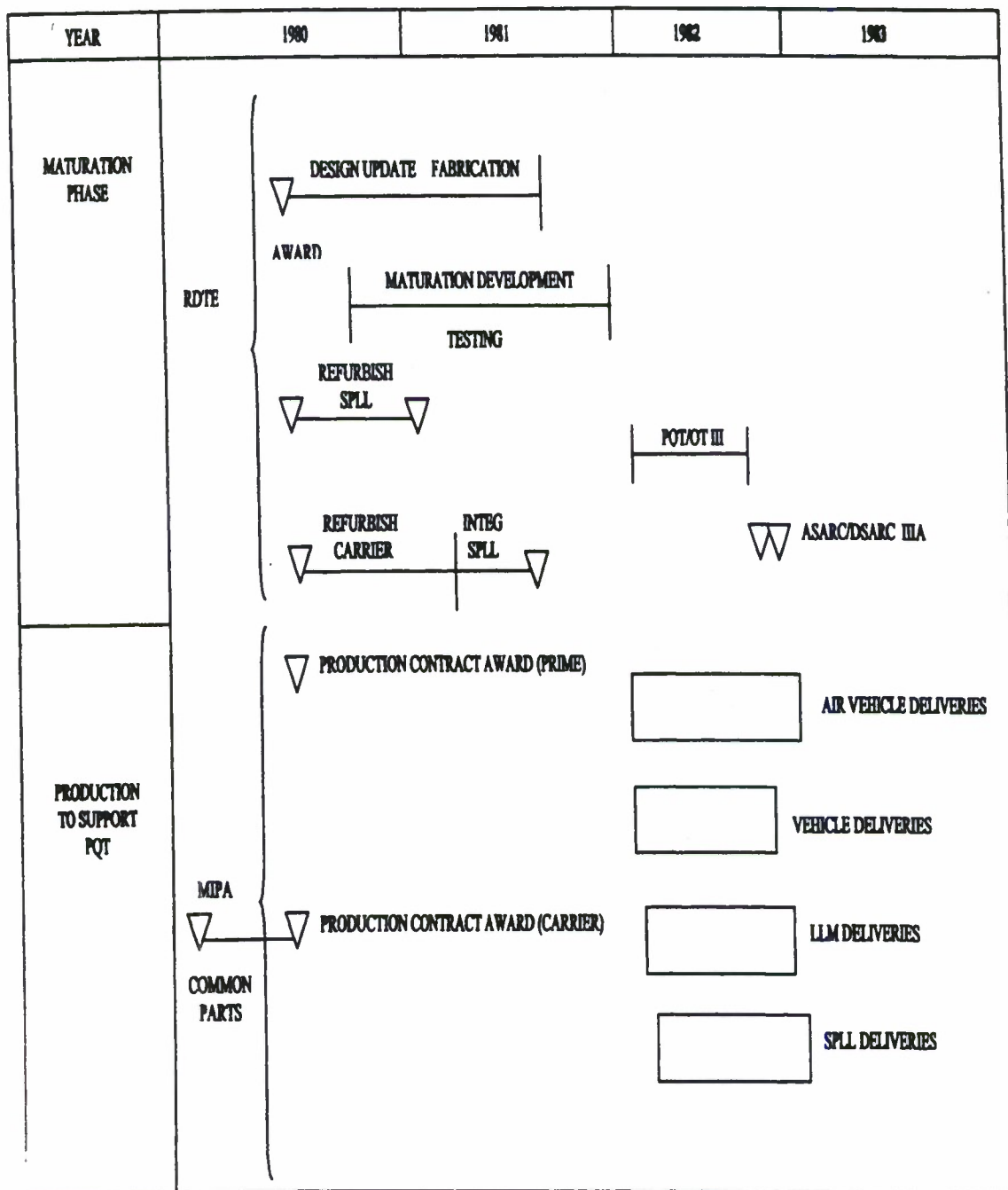


Figure 2 – Maturation/Initial production phase schedule

Award fee provisions for DTUPC goals were utilized during the validation phase. However, the huge incentive was the large production contract. In the competition to win the large production contract both Boeing and Vought demonstrated a willingness to expend company resources in excess of the contract funding in order to build competitive prototypes. This result could not have been achieved without the development of an effective competitive strategy that placed Vought versus Boeing in an extraordinarily high stakes competition.

In 1983 Seggel and his team shifted the strategy from competition to the incentive of a multi-year long term contract for the sole source producer, Vought. While the Army had originally envisioned a continuation of the use of competition during full scale production it became apparent through subsequent cost studies that this approach would not be cost effective. This was because the government would be required to fund the capital expenditures necessary to construct two production facilities. The loss in economies of scale would exceed the gains achieved by competition in pricing. Seggel reasoned that rather than relying on competition to keep the cost down, the project office could "lock in" Vought's low price with a five year firm fixed price contract. It was reasoned that a multi-year contract would allow Vought to purchase materials in quantity at a discount and to obtain leases at long term rates. A comparative study headed by Herman Oswell proved this point. The contract protected Vought from inflation by making necessary allowances. Vought benefited further from the fact that the contract guaranteed the \$1.236 billion in sales over five years. This elimination of the uncertainty over year to year changes in government sales proved a large incentive to Vought to lock in at the competitive price. Subsequent GAO estimates of saving resulting from this strategy ranged from \$180 million to \$209 million.

One of the major factors which contributed to achieving a low price per unit was the fact that the strategy for the maturation phase contract included low rate production. Thus, before the competition between Boeing and Vought was completed there were bids not only for the completion of engineering development, but also low rate production and facilities. This not only introduced significant competition into the initial pricing, it also insured a high degree of realism in the numbers. This was because when the competing contractors submitted their bids for the maturation phase the low rate production had to be bid in accordance with their DPUTC estimates. By setting the number of units relatively high for low rate production, losses would be incurred by the contractor if unrealistically low estimates were submitted. This strategy had another dimension. If the contractor gave low estimates and incurred a loss during low rate production, the government still had the option of giving a percentage of the high rate production to the second contractor. Thus, the penalty for underestimating was significant and this tended to insure valid estimates.

During this timeframe Seggel had observed a number of programs that had either been over budget, behind schedule, or were required to make performance compromises. He was determined that this would not happen with the MLRS project. To this end, Seggel and his team put extraordinary effort into the development of the RFP and the appropriate level of specification in the contracts. This effort resulted in the level of control that was necessary in order to keep the program on schedule and under budget. As Seggel observed:

You can hand the contractor a problem and say go validate this concept, and where is he going to run? He can run any place he wants to! No, we had to build the fences to make sure that he stayed on the path that was going to get us the system we wanted in the end. So we spent a lot of time doing that. It [the contract] was very carefully worked.

It is important to note, however, that Seggel and his team did not over specify. They understood that the proper parameters had to be incorporated into the contracts. However, they wanted to allow the contractor the optimal degree of flexibility so as to not inhibit innovation in designing to a concept requirement. This allowed for innovative technical solutions and trade-offs in order to meet specific contract criteria. Wilbur Cummings, the MLRS program manager at Vought observed, "Their ability to write the performance specs for this system was the best that I have ever seen. That was accomplished by Seggel and Richardson".

The combined result of these efforts produced a program that was on budget. In 1979 the estimated cost of each high rate production rocket was \$4,160 (1978 dollars). In 1983, this estimate had been reduced to \$3,282 (1978 dollars). This would result in a savings of approximately \$350 million. On the other hand, the costs associated with the SPLs rose. In 1979 the cost of each SPL was estimated at \$0.687 million. The 1983 estimate was \$1.196 million. However, the savings on the rocket costs not only compensated for the increase in the SPL costs, but allowed the Army to purchase over twice the number of SPLs originally planned.

Lesson 5: Effectively Designing the Competition

Seggel understood that if the competition between contractors could be designed properly, cost, schedule, and technical performance could be optimized. Seggel had been advised to allow the contractors to develop competing prototypes during the validation phase with minimal supervision by the project office. It was believed that competition alone would guarantee high levels of performance and cost effectiveness. However, Seggel believed that this approach was only partially correct. He knew that the engineers and scientists working in the MICOM laboratories had developed a high level of expertise during the MARS program. This base of expertise could be tapped during the validation phase to assure high levels of technical performance. The plan was to provide the contractors with general design characteristics and parameters. Contractors would then propose specific designs. These proposals would be reviewed and analyzed by the MICOM engineers. Great care was taken to assure that there was no cross fertilization between the competing contractors. Subsequently, the approved designs would be translated into prototypes by the contractors.

Under the terms of the validation phase contract, Boeing and Vought would be reimbursed for the costs incurred in fulfilling the contract. Because the contract was a cost plus incentive fee/award fee contract, if the contractors performed better than the cost target they would benefit financially. Furthermore, cost ceilings were imposed and therefore, both Boeing and Vought were required to fund any excess costs during the validation phase. Because the subsequent production contract was potentially so lucrative both contractors were willing to expend corporate R&D funds in the effort to produce a

competitive prototype. The schedule was non-negotiable and each firm was given 29 months to design and produce the prototypes and complete the competitive testing.

The validation phase schedule, established in the initial contract, included the various reviews and testing schedule. The performance evaluation criteria and the relative ranking of the criteria were provided to each of the competing contractors (see Appendix). This served as a guide to both contractors and encouraged the use of management by objectives. It is important to note that these criteria were developed by the project office and not by MICOM contracting personnel, because only they would have the necessary expertise to make these judgments.

The rockets and the LP/C costs represented over 70% of the MLRS system costs. The SPLs contributed only roughly 15% to the total costs. Realizing that cost effectiveness was the number one criterion in the selection process, both Vought and Boeing focused efforts on minimizing rocket costs. Each contractor was provided with the data that the Army planned to use to measure ammunition cost effectiveness. These data included a target array of over 500 targets, and the algorithms required to determine performance. This method provided each contractor with the ability to optimize rocket unit cost and the number of rockets required to destroy the target in order to achieve the optimal level of cost effectiveness.

The MLRS project office technical personnel observed the contractor's developmental tests, reviewed contractor trade-off analyses, participated in preliminary and final design reviews, and quarterly reviews. However, the project office personnel avoided providing advice to one contractor without providing identical information to the other. Thus, significant effort was applied to ensure a level playing field.

The Source Selection Evaluation Board (SSEB) scored each contractor's proposal and performance against the criteria described in the Source Selection Plan. The scores were then provided to the Source Selection Advisory Council (SSAC) for further analysis and application of the SSAC weights. The SSAC weights were not divulged to the SSEB, and therefore, only individual criteria scores were presented in the SSEB evaluation results. In retrospect, one might argue that the presentation of the weights for each criterion would have been advisable.

Based on these observations, it is clear that while competition required more R&D funds than a sole source contract, in the final analysis significant savings were realized. If MLRS had been a sole source contract, any cost overruns probably would have been paid by the government. Furthermore, an additional contribution to cost savings was the fact that competition kept the project on the ambitious 60 month schedule.

Lesson 6: The Primary Challenge for the Project Managers: Completing the Project Schedule on Time

The primary challenge for both Larry Seggel and Wilbur Cummings was the ambitious schedule. The original schedule for the validation phase and maturation phase, including low rate production, was 60 months. The actual schedule was 64 months. However, if it had not been for a UAW labor strike at FMC that affected the schedule for the carrier vehicle and a required change in the rocket diameter, the schedule would have been completed in 60 months. This was a very impressive accomplishment that was achieved because of several important contributing factors.

First, because significant work had occurred in the MICOM labs prior to the creation of the MLRS project office, many of the technical problems had already been solved or at least were less technologically uncertain. Seggel had a long association with Herman Oswald and had a fundamental understanding of all the major technological challenges. Furthermore, Vought had developed a significant level of expertise in most of the relevant technological areas and particularly, free rocket aerodynamics during the early 1970's.

In any project reducing technological risk is central to avoiding schedule slippage (and cost overruns). Risk may be reduced by selecting components or subsystems that have undergone at least one generation of development. This was partially the case with the development of MLRS. However, there were notable exceptions: the aerodynamic pressure generated electronic time fuze, the bomblet dispensing system, launch timing intervals, free rocket aerodynamics, achieving accuracy, and other development challenges. In any case, technological knowledge or the technological readiness level was sufficiently advanced in each of these areas that effort could be focused earlier in development on each of these problems in order to remain on the ambitious schedule. This is where early work in the RDEC labs and work in the early 1970's at Vought paid off. As a result of a probabilistic risk analysis, Seggel and his team knew where the potential problems affecting schedule were on the PERT critical paths. They worked with the contractors in keeping the proper focus on these elements in order to eliminate their potential impact and remain on the schedule. Vought assigned teams with some of their most talented engineers to these design challenges. Many of these individuals had been working in these technological areas at Vought since the early 1970's.

The maturation phase that was incorporated into the MLRS project was uncommon to most acquisition plans. Low rate production usually occurred after an engineering development phase in which the prototype design was finalized. In the case of MLRS contingency plans called for a two year engineering development phase to be inserted between the validation and maturation phases if this was found to be necessary. However, the validation phase was so successful, and testing revealed relatively few problems, so the ASARC and the DSARC determined that the program could proceed directly from the validation phase to the maturation phase and low rate production. The ability to avoid an engineering development phase after the initial validation phase can be attributed in part to the maturity of the technology employed in MLRS. In this sense, the early R&D work at MICOM paid off.

Dennis Vaughn, who succeeded Lawrence Seggel as Deputy Project Manager in 1987, observed another factor that contributed to the performance in meeting the schedule. He noted that the design of the competition in the validation phase with a fixed date for testing tended to force each contractor to focus on meeting the requirements. This eliminated the tendency toward continuing nonessential innovation during development with the inevitable slippage in the schedule. Seggel realized that innovative ideas should be considered for future versions of MLRS, but that it was critical to the US defense needs to field the system on schedule. He was therefore vigilant about controlling what Dennis Vaughn labeled "pie in the sky" engineering changes. Seggel was continually approached by TRADOC and by high level Pentagon officials with suggested changes during the validation and maturation phases. This was a constant source of challenge to Seggel and he handled these suggestions astutely. Innovative ideas could be

considered for later versions as preplanned product improvements, but the current program had to remain on schedule. Therefore, only essential engineering changes were incorporated which were necessary to the functionality of the system to meet basic performance requirements. Both Seggel and Vaughn maintained that two of the problems that get many projects off schedule are requirement instability and funding perturbations. In other words, the user keeps changing the requirements and the annual funding keeps changing. These problems are ultimately dysfunctional in project management and the MLRS project was able to avoid these successfully.

The validation phase and the maturation phase were characterized by elements of concurrent engineering. This also tended to compress the schedule. During the validation phase production planning was already in progress. During the maturation phase Vought was still making engineering changes and still testing, but simultaneously equipping the production facility for low rate production. Production equipment was put in place first for those components that were needed first. In cases where the production equipment was not ready Vought relied on outsourcing to stay on schedule. Vought had teams of engineers simultaneously working on different competing solutions to a single problem. When the problem was difficult, as was the case with the warhead device that dispersed the bomblets, they assigned their best engineering talent to the problem.

Lesson 7: Achieving Effective Integration Across Organizational Interfaces

An important factor that contributed to the success of the MLRS project was the level of effectiveness that was achieved in the integration or coordination across organizational interfaces. Figure 3 presents a chart of all relevant government and contractor organizations during the timeframe of development.

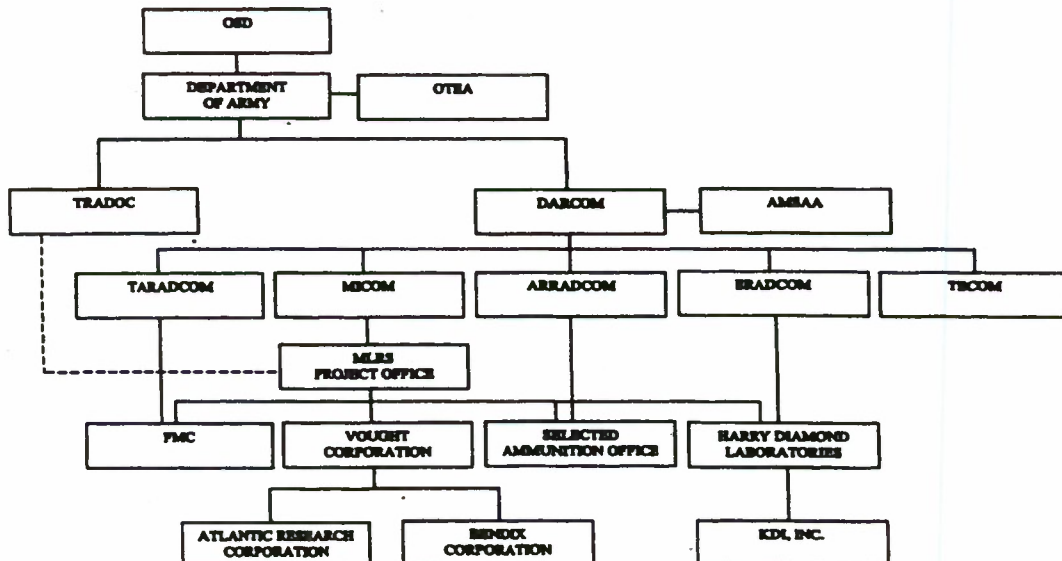


Figure 3 – Overall (government/contractor) organization for MLRS

The organizational chart for the MLRS project office is presented in Figure 4 and the Vought Corporation organization for MLRS production is presented in Figure 5.

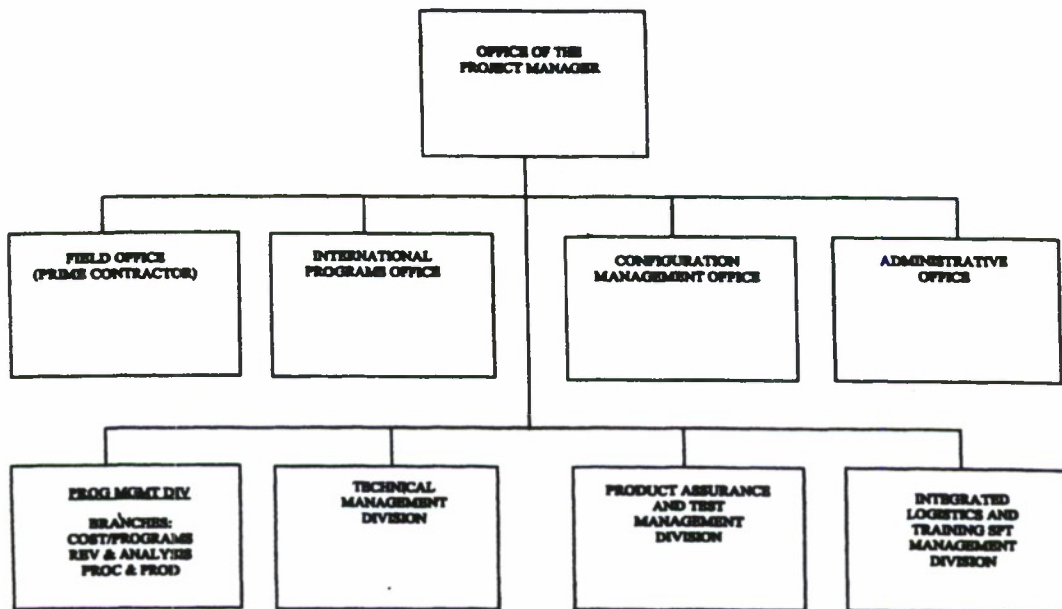


Figure 4 – MLRS Project Office organization at MICOM

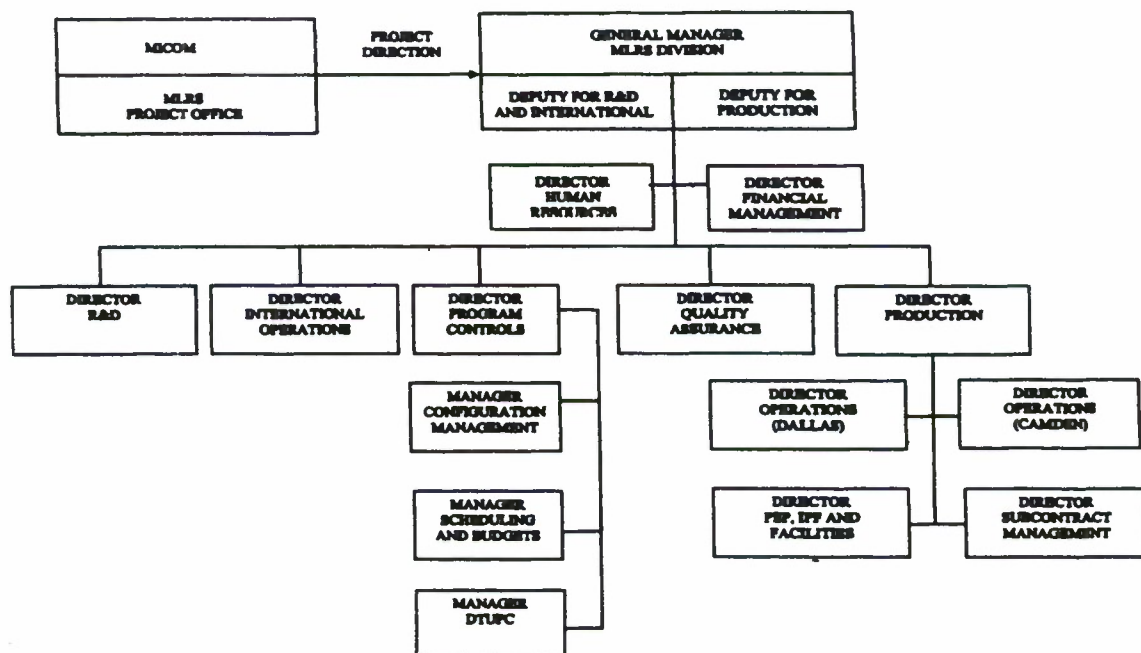


Figure 5 – Vought Corporation organization for MLRS production

To assure effective integration the MLRS project office developed a detailed development program plan that clearly defined the objectives, presented the schedules, and established the responsibilities for the various participants in the program. This not only included the contractor, but TRADOC, and the various test, logistics, and training agencies. Like a score for a symphony, the development plan showed unequivocally who was to assume each responsibility, when, where, how, and on what hardware. This document was the common basis for understanding and planning among all of the participants. Early in the program the development plan was updated every six months. Later in the program annual updates were implemented.

Wilbur Cummings, the general manager of the MLRS division at Vought initially created an organization in which managers over each function at the MICOM project office would have their direct counterpart in Vought's project organization. This organization worked well to facilitate communication and coordination between the liaison counterparts on the government and contractor sides. The concept of integrated product teams did not emerge at MICOM until the 1990's. However, even though MLRS development preceded the implementation of this concept, Wilbur Cummings described the same principle implemented informally between Vought and the MICOM MLRS project office. Cummings suggested that the various MLRS groups at MICOM were involved from the earliest stages in decisions that involved design or production problems. Hence, the relationship was not merely one of reporting but rather it could be characterized by joint problem solving. Dennis Vaughn observed that this even occurred to a degree during the competition between Vought and Boeing. In order to be sure that information was not passed between one contractor to the government and then to the other competing contractor, the project office assigned engineers to separate groups associated with each contractor. Thus, the interface between the contractor and the government project office was very functional.

The interface between the project office and TRADOC was also managed very effectively from the beginning. TRADOC was represented in all major program reviews with the contractor and testing. They were also represented during the international negotiations with the NATO partners. During development Vought and the MLRS project office worked closely with the user (personnel from Fort Sill) in the human factors area to improve the user interface. During early deployment the project office systematically collected data from the field units and utilized this information for subsequent improvements. Larry Seggel described the relationship between Vought, the user, and the project office as an "open book". In short, no major decisions were made without user involvement.

The international involvement of France, West Germany, and the UK created more complicated integration problems. In fact, Larry Seggel observed that the most significant issue in the development of MLRS was the management of the international partnership. For example, with the tactical fire control system each nation had unique features. Therefore the launcher had to be capable of responding to the fire control organization of each nation separately, yet interchangeably. The MLRS project office created integrated working groups to solve these problems. These multi-organizational teams would include engineers from the relevant country (who were collocated in Huntsville, Alabama), project office personnel, and the Vought engineers. Their design solutions would then be submitted to the executive management committee that consisted

of the program managers in each country. Following their approval or modification the directives would then be submitted to Vought to implement. This organizational solution to this problem of integration worked very effectively.

Another important characteristic of the interface between Vought, the project office and subcontractors was integration that was achieved through concurrent engineering. Specifically, design for manufacturability played an important role in reducing the cost per unit and in facilitating schedule performance. Design/cost teams from Vought, the government, and in some cases subcontractors would coordinate to determine how each component could be produced in the most cost effective way. Thus, design decisions were influenced by cost considerations and manufacturing processes.

Based on these observations it is apparent that optimal forms of organizational modes of integration were utilized to achieve the necessary coordination across multiple organizational interfaces. However, the management research literature has shown very clearly that the use of the appropriate organizational modes of integration is a necessary but not sufficient condition. What is also required is the necessary level of cooperation between individuals across these interfaces. If organization modes of integration are in place, but cooperation and trust are deficient, coordination problems will inevitably result. In the case of MLRS, Wilbur Cummings from Vought and Dennis Vaughn from the project office both observed that cooperation was exceptional. In no case did an adversarial relationship ever develop. This was not accomplished by accident. It is to the credit of Cummings, Seggel, Vaughn, Richardson, and other key managers that cooperation was facilitated through a concerted effort, despite numerous development and production problems.

Lesson 8: An Effectively Designed Test Program Reduces Subsequent Problems During Production

The test program for MLRS was designed to support the accelerated program schedule. During the validation phase testing was more comprehensive than what would have usually occurred during that phase. During the validation phase, instead of testing on surrogate hardware that simulated technical and operational characteristics, prototype hardware was designed, fabricated, and tested. The system designs that were tested during the government scored testing represented the production designs. Minor design changes that were identified during the testing at the end of the validation phase were implemented during the maturation/initial production phase.

The project office formed two Test Integration Working Groups during the validation phase. Boeing was a member of one group and Vought was a member of the second group. Other representative members of the groups included the MLRS project office, AMSAA (independent testing evaluator), OTEA (operational tester and independent evaluator), TECOM (development tester), MICOM (maintenance planning), LEA (logistics), TRADOC (combat development/user), the M-42 submunition developer, FVS (the carrier developer), and Harry Diamond Laboratories (the fuze developer). Because of the international nature of the program an international Test Integration Working Groups was formed with representation from the participating nations.

In the operational testing at the end of the validation phase OTEA, the Army test and evaluation agency, conducted three batteries of tests. Operational Tests I and II (OT I and OT II) were non-firing tests that were designed to assess reliability, maintainability,

and survivability of the system. For Operational Test III (OT III) Boeing and Vought each fired 12 rockets at White Sands Missile Range.

Because the maturation /initial production phase occurred concurrently, the testing schedule was compressed. The maturation development testing and the production qualification testing were done jointly between Vought, subcontractors, and the government. While the problem with the fuze was a relatively large problem, relatively minor problems with the SPLL were identified and corrected. Because problems were identified during low rate production it may have been beneficial to increase the depth of testing during the validation phase. In fact, Wilbur Cummings observed that the most significant management challenges and issues during the program revolved around engineering changes during production. These problems were identified and resolved by assigning teams to each problem and concurrently addressing the production issues. In any case, with an accelerated program, such as MLRS, the elimination of problems during low rate production would be a difficult objective to achieve.

Lesson 9: Continuity and Stability in Funding and Personnel

A factor that cannot be overemphasized which contributed to the success of the MLRS program was the continuity and stability of funding. Any number of organizations had the power to terminate or at least curtail the program. These included the Field Artillery, the Army Chief of Staff's office, the Secretary of the Army's staff, TRADOC, the Office of the Secretary of Defense, and Congress. The continuity and the stability of funding were not achieved without a continuing vigilant effort. Project managers Heitzke, Masters, Steimle, Hatchett, Cianciolo, O'Neill, and Hurst all focused their energies on persuading the appropriate agencies and individuals to maintain the necessary level of funding support for the project. As a consequence, cyclical variations and idiosyncratic funding threats were successfully avoided.

In addition to stability in funding, Seggel, Vaughn and Cummings indicated that stability in personnel played an important role in maintaining program momentum. At Vought, turnover among key personnel was low during the period of development through the transition to production. Vought did not make it a practice to pull people off the project to work on other contracts. With the same group of engineers following the program through development, qualification, and production, disruptions due to personnel changes were minimized. On the government side, stability in leadership in the MLRS program management office was an essential contributor to success. There was almost no turnover during the first twelve years of the program among the division level managers and Deputy Project Manager. Stability can lead to stagnation unless highly talented people are involved. When assembling his team Seggel sought people who were energetic, innovative, and self motivated. Turnover among technical professionals with highly specialized (system specific) knowledge always has hidden costs. In the case of both Vought and the MLRS project office, these hidden costs were minimized.

Conclusion

The ultimate proof of the efficacy of any weapon system is the actual results during combat. During Desert Storm personnel from MLRS units reported that the system actually exceeded expectations in the Gulf War. MLRS proved to be more

effective against harder targets than what had been originally estimated. Combat units reported that when the Iraqis fired on American units with artillery, and massive MLRS fire was returned, in almost every case silence ensued. Captured Iraqi soldiers referred to the devastation caused by the 644 grenades per rocket as "steel rain". With the exception of armored vehicles, each rocket would totally destroy everything within a soccer field sized area. The destructive and the psychological effect of this level of devastation on the Iraqi Army contributed significantly to their total defeat in the Gulf War.

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Endnote

¹ This case utilized interviews from some of the same respondents as the Gudmundsson reference. It also overlaps through 1986 with the Gudmundsson case. However, the issues examined in this case study, in terms of lessons learned, vary significantly from the reference noted above so as to warrant a separate case study.

APPENDIX
MLRS PROPOSAL EVALUATION CRITERIA

Criteria used for evaluation of proposals for the MLRS Maturation/Initial Production Phase are identified below in their ranked order.

Criterion 1: Ammunition Cost Effectiveness

The score for Criterion 1 was based on an evaluation of the total ammunition cost required to defeat the government's target array, as specified in the RFP.

Criterion 2: Maturation and Full Scale Development Proposals

Evaluation of the proposals was performed in four areas - technical, cost, operational, and management. The following weights were utilized in scoring: technical, 30%; cost, 35%; operational, 20%; management, 15%.

Criterion 3: Low Rate Production Proposal

Evaluation of the low-rate production proposals was performed in three areas -- technical, cost, and management. The following weights were utilized in scoring: technical, 30%; cost, 50%; management, 20%.

Criterion 4: Mission Cycle Times

Scoring of this criterion was based upon the times demonstrated during operational testing.

Criterion 5: Operational Utility

This criterion was scored using the following factors: investment and support costs; human engineering; logistic support; survivability growth potential; operator skill/training requirements; safety.

Criterion 6: Initial Production Facilities Proposal

Evaluation of the initial production facilities proposals was performed in three areas -- technical, cost, and management. The following weights were utilized in scoring: technical, 30%; cost, 45%; management, 25%.

Criterion 7: Validation Phase Contractual Performance

This criterion was scored based on information from the MLRS Project Office. The information was based on a continual assessment accomplished over the life of the Validation Phase contracts to determine the achievement of program and cost objectives; i.e., contractual performance. The assessment of each offeror's Validation Phase management performance was made through award fee evaluations. Assessment of attainment of Validation Phase cost objectives, i.e., cost performance, was made through analysis of cost performance reports. The following weights were utilized in scoring: management performance, 50%; cost performance, 50%.

Criterion 8: Reliability and Maintainability

The purpose of the reliability factor was to assess and evaluate the quantitative reliability achievements during the Validation Phase. Data utilized was obtained from the development and operational tests. The purpose of the maintainability factor was to estimate and evaluate the quantitative maintainability achievements of the Contractor Furnished Equipment designs for all the SPL. Two maintainability parameters --

mean time to repair and maximum corrective maintenance time -- were evaluated at each of two maintenance levels, organizational and direct support. The following weights were utilized in scoring: reliability, 70%; maintainability, 30%.

Criterion 9: Conformance to System Specifications

The offeror's Validation demonstration hardware was evaluated on a point-by-point basis against the requirements of the MLRS system specification. The evaluation considered only those specification elements not scored under other criteria. The results of government and offeror testing, together with the design description in the Maturation/Initial Production Phase proposal, served as the basis for this evaluation. Scoring was done using a listing contained in the Source Selection Plan. If, through no fault of the offeror, an item could not be scored, then that item was not scored for either offeror and remaining weights were adjusted to a 100 point basis.

AN/TAS-4A NIGHT SIGHT

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I. BACKGROUND:

The TOW (tube launched, optically tracked, wire guided) system was designed, manufactured and fielded to provide a man-portable capability against enemy armor. The initial system was a ground variant consisting of the missile, the launch tube, the tripod for the launch tube, the missile guidance set, and the optical sight and missile tracker. The system evolved due to changes in technology and the change in the threat armor characteristics.

Subsequently, the TOW system was expanded to a vehicle mounted system, such as the Improved TOW Vehicle (ITV) M901, ¼ Ton Truck, Utility M151 (jeep), Bradley Fighting Vehicle (BFV) and later to the Cobra helicopter. In all, the theory of operation was the same but the hardware and software evolved as technology advanced. Some of the most significant changes were in the tracking and guidance for the missile and the variants of missiles designed to address the escalating threat.

The TOW is a well-established system that was first fielded in 1970. There were two basic reasons for adding the night sight viewer/missile tracker to the system. First, was the capability to view targets at night and in some inclement weather conditions. Second, as a counter-countermeasure. There was a threat of a wide beam xenon jammer that could severely reduce the effectiveness of the system. Therefore, the addition of a night vision device would increase day/night capability and allow optical countermeasure hardening by operating in another waveband separated from the near infrared xenon wavelength.

In 1973 the TOW thermal night sight (AN/TAS-4) program began. Problems encountered in Vietnam with night firings also affected this program. The TOW system's daylight combat operations in 1972 were a dramatic success, but the airborne XM26 TOW had limited usefulness at night. The first night firings in combat failed because the gunners were blinded first by the bright infrared source, then by flares. A filter allowed night firings without blinding the gunner, but it was still almost impossible for even experience gunners to locate a target at night. Several misses also occurred because the gunner was unable to see the target while guiding the missile. Night combat experience in Vietnam showed the need for a passive night vision system for target detection and tracking before the airborne TOW system had an effective night capability. Refer to Appendix A for a detailed description of the TOW system components.

II. KEY ORGANIZATIONS AND PLAYERS

The operational requirement for the TOW ground system was developed by the U. S. Army Infantry School at Ft. Benning, Georgia. Within the Infantry School there was a Director of Combat Developments (DCD). It was this DCD that produced the Qualitative Material Requirement (QMR) stating the "performance" needs against enemy armor. These needs not only drive the development of systems, but also the testing of systems against relevant targets to prove performance.

The TOW Project Office then took the operational requirements, as mentioned above, and converted these to technical requirements defining the technical performance of the system. The technical requirements were derived by system engineering analysis by the TOW Project office Engineering Division headed by Mr. Coy Jackson. The Project Manager was Col. Byron Powers and his Deputy Project Manager was Mr. George Williams.

The U. S. Army Missile Command (MICOM) Research, Development and Engineering Center (RDEC) provided the government technical support for the TOW Project Office and all project offices at Redstone Arsenal, Alabama. The RDEC Director was Dr. William McCorkle.

The Night Vision and Electro Optics Laboratory (NVEOL) was a research and development laboratory under the U. S. Army Electronics Command (ECOM). The lab director was Dr. Louis Cameron. Mr. Albert Van Landuyt was the lead engineer for the development of missile night vision devices. Mr. Robert Nystrom was the head of the Test and Evaluation efforts at NVEOL for Mr. Van Landuyt and the Missile Team.

Kollsman Inc was and still is a manufacturer of night vision devices. Kollsman produced night sights of the "Dragon" tracker systems (SU-108) and the AN/TAS-4 prior to being selected to produce the AN/TAS-4A for the TOW 2 system.

III. INTRODUCTION OF THE AN/TAS-4A INTO THE TOW-2 SYSTEM

1. DEVELOPMENT PHILOSOPHY

The original development of 7.5 to 11.6 micron viewing devices was an undertaking of the U.S. Army Night Vision Laboratory, Fort Belvoir, VA. Before the long wavelength infrared detector/Dewar system was developed, night vision devices consisted of image intensifiers. There was an attempt to develop a common night acquisition system for both the Army and Navy, hence the nomenclature of AN/TAS (Army-Navy Thermal Acquisition System). In September 1975 Texas Instruments received a contract for developmental / operational testing hardware and follow-on full scale development of the Man portable Common Thermal Night Sight (MCTNS) The first AN/TAS-4 night sight was strictly a viewer. There were no signal outputs that could be used to "close the tracking loop." Without signal outputs, the night sight is a viewing device only. Once output signals are available and the target signature in the infrared spectrum of interest is above a preset threshold, the position difference of the target and the

thermal beacon on the back of the missile can be minimized (close to zero). This minimization process is what is meant by "closing the tracking loop."

The TOW night sight program was part of the competitive Man portable Common Thermal Night Sight (MCTNS) Program. The MCTNS was the answer for the Qualitative Material Requirement (QMR) for the Infantry ground mounted Heavy Antitank Weapon (HAW), Medium Antitank Weapon (MAW), and the Light Antitank Weapon (LAW). These are the TOW, Dragon and LAW respectively.

The task that NVL had was to provide test systems for the TOW missile system, the Dragon missile system and the long-range night observation device. The competing contractors were:

Texas Instruments (TI), Dallas, Texas

Hughes Aircraft Co. (HAC), Culver City, California

Phillips Broadcast Equipment Corp. (PBEC), Mahwah, New Jersey

TI and HAC provided newly and specifically designed TOW and Dragon systems for evaluation. The PBEC was tasked to provide an Extended Range AN/TAS-3. The AN/TAS-3 was a thermal night sight developed and tested for use on the Dragon missile system. The Extended Range AN/TAS-3 was an up-graded TAS-3. It incorporated thermal electric (TE) cooling and a larger afocal lens to provide the required resolution of objects in the field of view. This system was eliminated because of its inability to provide an adequate target signature for engagement at maximum range.

The systems coming out of this program were later designated as: AN/TAS-4 for TOW, AN/TAS-5 for Dragon and AN/TAS-6 Night Vision Sight, Long Range (NODLR) for battlefield surveillance.

In addition the MCTNS was used as the entry point for the Army's Common Module (CM) Program for thermal night vision sights.

In November 1978 Texas Instruments delivered the first AN/TAS-4 TOW production night sight. In September 1979 deployment of the AN/TAS-4 production night sight began with "fieldings" to training bases in CONUS and USAREUR. Vision Sight Infrared AN/TAS-5 for Dragon and Night Vision Sight Infrared AN/TAS-6 or the Night Vision Sight, Long Range (NODLR) used for battlefield surveillance.

2. DEVELOPMENT OF THE AN/TAS-4A

The AN/TAS-4A effort itself was started as the result of a discovery by NVL during a competitive selection shoot off between TI and HAC entries for the TOW night sight. The NVL found that the thermal night sight (AN/TAS-4) was able to acquire targets at maximum range

through the ground haze at Test Area One on Redstone Arsenal Alabama while the day sight/tracker would lose the missile xenon beacon before maximum range under the same conditions. Hence, the need to provide guidance to the missile under these and other adverse atmospheric conditions using the thermal sight was satisfied.

Going from a target acquisition and tracking system to a missile guidance system required a totally new specification. Since the TAS-4 did not meet the new specification of being able to guide the missile to a target, there was a retrofit line set up at TI where TAS-4 (thermal sights) were returned from the field for the upgrade to an AN/TAS-4A.

The importance of the technology to the prime contractor is in the application to a tactical problem. Very few night sights were developed and fielded as viewing devices. The number of systems, like the AN/TAS-4A that were built and fielded as tracking devices was quite large. The technology was already at hand and it was straight forward engineering to take the tracking signals out of the night sight to the digital missile guidance set.

Therefore, the TAS-4 series of night sights were developed to be target acquisition and target tracking devices. The advent of the TAS-4A and 4C used with the TOW 2 weapon became supplemental or back-up missile guidance devices.

The AN/TAS-4A was developed to be a part of the TOW-2 tracking system. It has a digital output that went to the missile guidance set (MGS) and the MGS eventually became a digital MGS or DMGS. The AN/TAS-4 night sight was designed to have a factor of ten improved sensitivity compared to the optical sight for equal missile beacon size. This equaled improved system performance in adverse environments. The night sight design was based on target acquisition required by the User as stated earlier. In short, this means the detection, recognition and identification of targets at specified ranges, specified target size, and specified radiometric and atmospheric conditions. The operational requirement was to detect a tank target that had not been operated for 8 hours, at a distance of 3000 meters, recognize this target at 2200 meters, and identify this target at 1600 meters during the hours of darkness. These operational values are then translated into engineering values as design criterion.

When technology was to be inserted into the TOW system the system engineer in the TOW Project Office ensured the integration and compatibility of all components. Therefore, it was the duty of the weapon system engineer to assist the technology developers in understanding the technical requirements. Along with these technical requirements, the system engineer ensured the technology was matured to the proper level for inclusion into the system. Insertion of technology that is too immature can lead to increased development cost and slips in schedule. Therefore, the maturity must be monitored to select the proper point of insertion into the system. The system engineering responsibility was never passed to NVL or the contractors and remained in the TOW Project Office for the AN/TAS-4A and the TOW-2 system.

In order for the AN/TAS-4A to track the missile in flight a thermal beacon was required. There were technical problems and engineering development required to make the thermal beacon a reality. The thermal beacon occupies a small space on the back of the missile and provides a 7.5

to 11.6 micron source for the night sight/tracker to follow. This development began in 1980 and was more difficult than the development of the AN/TAS-4A into a tracker. Hughes Aircraft Company worked with a vendor to design and manufacture the thermal beacon. The thermal beacon was required to have the same intensity for equal area compared to the xenon beacon used with the optical tracker. The thermal beacon had to "burn" for 25 seconds (time of flight was 22 seconds to max range). A shutter was required to block the thermal beacon at a rate of once per second allowing the night sight and tracker logic to identify the missile in the presence of the thermal background.

Once the TOW-2 system was developed and tested there was a technical integration of the various missile variants into the launch tube and digital missile guidance set. Each missile variant had to be recognized by the system and the missile guidance software for each variant must be matched to the missile type. The solution was simple and reliable. A resistor was placed in the missile so that its value could be read by the DMGS. The value dictated the missile type and the guidance equations to be used to guide the missile to the target.

The development of the total TOW-2 system to include the AN/TAS-4A night sight was accomplished in a fully open manner. The Project Office personnel, NVL personnel, contractor personnel, and the user at Ft. Benning, Georgia all were free to discuss the status of the system development and problems that existed. The user was closely coupled with the Project Office and supported the development all the way. However, communication by the heads of the organizations involved in the development and fielding of the AN/TAS-4A was not always positive. This created some problems in overall coordination and consensus. There was no Integrated Product Team (IPT) as we know it today, but rather a group of "old guys who knew each other for years", according to Coy Jackson.

In January 1980 the AN/TAS-4 TOW night sight achieved Initial Operational Capability (IOC) and in September of 1980 the first FORSCOM units received the TOW night sight.

3. TECHNOLOGIES FOR THE AN/TAS-4A

There are two classes of technology to be considered: field based technology and organization based technology. Field based technology is new, state-of-the-art technology that is new to the field, new to everyone. Organization based technology is new to an organization in its application but may not be new to other organizations. Under these terms the focal plane arrays for the AN/TAS-4A and subsequent versions are not field based technology but are organization based in that they are being used for a new application in the TOW-2 system. This same analogy can be made for the Thermal Beacon that is the infrared source for the tracker and helps to develop the closed loop guidance of the missile.

Critical to any systems engineering process is the maturity of the technology to be used. The exploration of concepts is usually accomplished through multiple short-term studies. Development of these studies is expected to employ various techniques including the systems engineering process that translates inputs into a viable concept architecture whose functionality can be traced to the requirements.

If the details of the concept require definition, i.e., the system has yet to be designed and demonstrated, or the system appears to be based on technologies that hold significant risk, due to their immaturity, then it is likely that the system will proceed to the systems engineering process phase of Component Advanced Development. The fundamental objectives of this stage of development are to define a system level architecture ("system" here can be a component of the overall higher level system) and to accomplish risk-reduction activities as required to establish confidence that the building blocks of the system are sufficiently well defined, tested and demonstrated to provide confidence that, when integrated into the higher level assemblies and subsystems, they will perform reliably.

Risk reduction activities such as modeling and simulations, component testing, bench testing, and man-in-the-loop testing are emphasized as decisions are made regarding the various technologies that must be integrated to form the system. These risk reduction activities allow the maturity of the technologies to be assessed. These assessments, in terms used today, are Technology Readiness Levels. For the technologies needed for the AN/TAS-4A this assessment of technology readiness varied depending on whether the technology to be employed was already in use some where else or needed to be developed "from scratch".

The following technologies were critical to the night sight development and operation and allowed the night sight to be integrated into a total system that could be tactically deployed.

FOCAL PLANE DETECTOR ARRAYS: The detector array used for the TAS-4 and all MCTNS systems was the smallest for the Common Module Detector Dewar Assemblies. It consisted of 60 vertically aligned detector elements, which are sensitive to infrared radiation in the spectrum of 7.5 to 11.6 microns when cryogenically cooled to 77 degrees Kelvin (K) [-193 degrees Centigrade (C)]. The detector element array was packaged in a Dewar for thermal insulation. As the infrared image is scanned across the array, each detector produces small variations in current, which corresponds to variations in temperature of the objects in view. The variations are coupled to a video preamplifier then to a video post amplifier to be converted to a video signal. The detectors are capable of resolving small objects with temperature differences as little as 0.2 degrees Centigrade. The TAS-4A Night Sight WFOV has a resolution of 0.50 milliradian (mr) and the NFOV has a resolution of 0.167 mr. These resolutions specifications provide the night sight with the ability to resolve target details as small as 20 inches in the WFOV and 6.6 inches in the NFOV at 1000 meters range.

SMALL SIZE HIGH POWER THERMAL BEACON:

In order for the night sight and the missile guidance set to track and guide the missile a thermal beacon had to be developed for the missile. The thermal beacon had to be small, on the order of the xenon source, and high powered to present a high signal to clutter ratio to the detector arrays. A shutter was provided to block the thermal beacon once each second and then expose it again to further aid the night sight and missile guidance set to recognize and guide the missile. A picture of the TOW-2 missile showing the thermal beacon placement is shown in Figure 1.

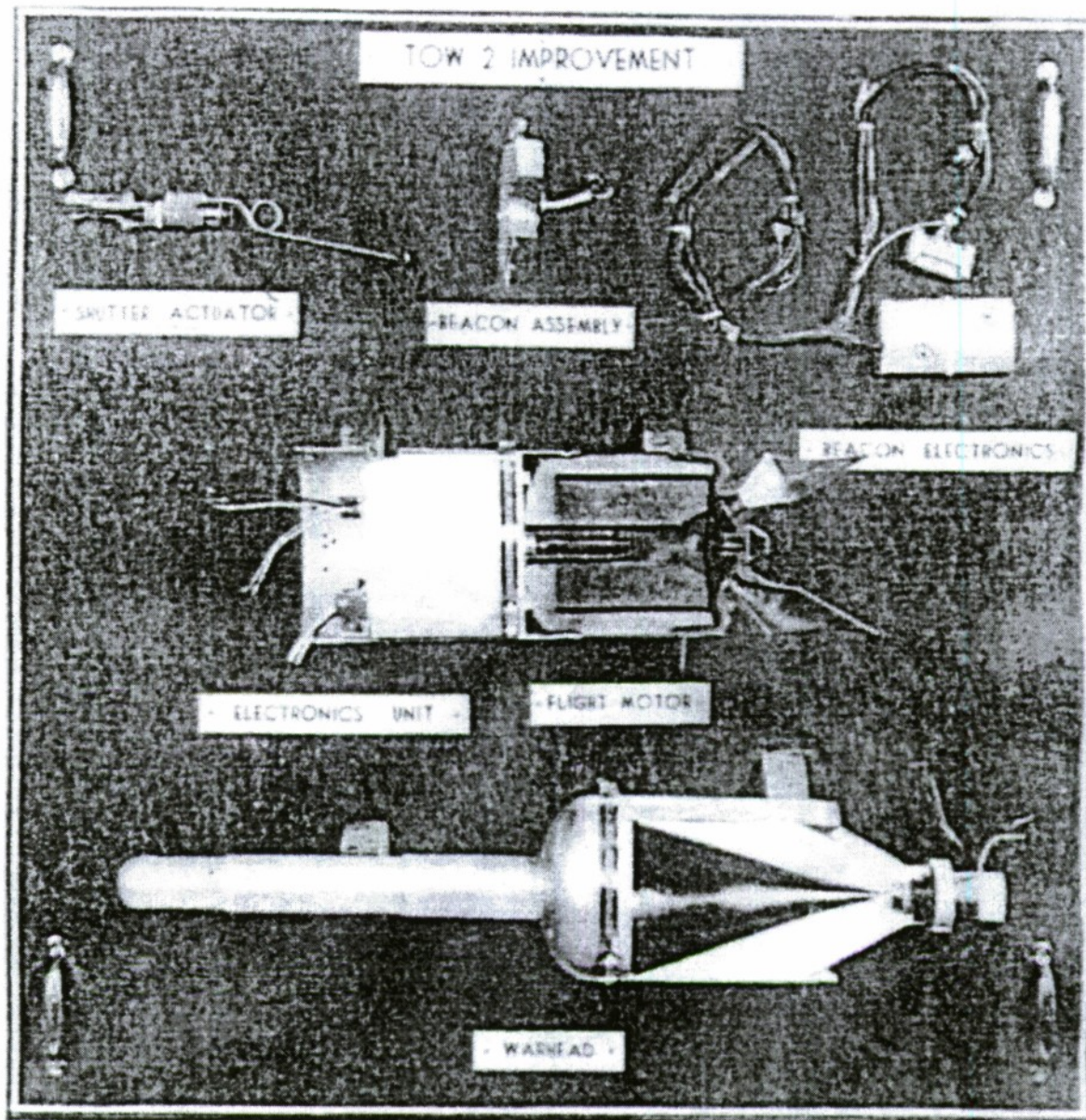


Figure 1. TOW-2 Missile Components

4. TESTING

The test approach taken by the prime contractor and project office team was very thorough. Components were tested at the specified environmental, shock and vibration levels. The missile was "flown" on a missile sled prior to flight-testing. The flight tests were accomplished in several environments to include a target with no countermeasures, a target with countermeasures, hot and cold conditions imposed on the system, as an example. The TOW system prime

contractor, Hughes Aircraft Co., also developed and operated a hardware-in-the loop (HWIL) facility in Tucson to test hardware and software compatibility. An important out-come of the HWIL facility was the six degree of freedom (6DOF) model of the TOW-2 system. The hardware-in-the-loop facility placed the TOW-2 system (tracker, missile, day sight, and night sight) in an environment where the system believes it sees a real target and the missile flew toward this target depiction. This facility not only "exercised" the hardware and but also the guidance software in the digital missile guidance set. A product of the HWIL facility was a high fidelity simulation of the system. With this model or simulation many test runs were made using a computer instead of expensive flight tests on a test range using real missiles and real targets. The AN/TAS-4A was developed as a part of the TOW-2 Development Program. During the 3-year development program 100 TOW-2 missiles were fired at Test Area One on Redstone Arsenal, Alabama. The hardware-in-the-loop simulation was updated periodically during this time based on test results and was validated near the end of the development program. The Initial Operational Capability date for the TOW 2 program was October 1983.

All testing was done to prove the system was qualified and could proceed to low rate initial production (LRIP). The system testing and development remarkably stayed on scheduled.

5. SCHEDULING AND CONTRACTING

The AN/TAS-4A night sight equipment sets produced by Texas Instruments (TI) had a very high cost (approximately \$75,000). In an effort to lower the night sight cost, Kollsman Inc won the Night Vision Laboratory held a second source competition and this competition. Kollsman was buying detector/Dewar assemblies from Honeywell according to the government specification in the Technical Data Package (TDP) for detector-Dewars used in the AN/TAS-4. The required performance specification for the detector/dewar combination in the AN/TAS-4A was to detect targets of interest that were two tenths (0.20) of a degree (centigrade) above the background temperature. A large percentage of the night sights built by Kollsman had reduced sensitivity that only allow viewing of objects that were as much as four tenths (0.40) of a degree above the background temperature which resulted in a reduction of viewing range of 400 meters. This is a serious degradation in a wartime setting. The TOW Project Office, with the concurrence of the Army Materiel Command (AMC), refused to accept AN/TAS-4A night sights built by Kollsman Inc. that did not meet the system specification. The problem was the sensitivity of the detector/dewar and the possible loss of the thermal beacon signal under adverse conditions. However, without waiver approval Kollsman was contractually obligated to use items specified in the TDP even if they did not meet government specifications. Kollsman applied for formal waivers/deviations and "did not hear from the government labs that held the contracts".

The NVL was laboring to enforce the integrity of the contracts with TI and Kollsman to produce quality systems needed for fielding in the TOW-2 system. The US Army Missile Command (MICOM) Research, Development and Engineering Center (RDEC) was concerned with meeting the commitment to fielding on schedule. To preserve the Tow Project Office (TPO) fielding

schedule, MICOM decided to take control of the management of the contracts. In order to meet the TPO fielding schedule MICOM granted waivers and deviations to both TI and Kollsman for the production of the AN/TAS-4A. Some of these changes resulted in printed circuit cards with the same part numbers but the cards were not interchangeable between a TI and a Kollsman built units. Before long the configuration management personnel at MICOM were trying to track down the changes in the AN/TAS-4A and they found at least ten different versions. There were differences in items, part numbers and federal stock numbers. Kollsman was required by their contract to notify the Government of changes and there were no formal records. Eventually an AN/TAS-4C (Hybrid) system was created. This system is able to utilize the greatest majority of the many different TOW unique cards and modules.

Kollsman Inc. preserved records of everything built with complete documentation of all requests for engineering change proposals (ECP) or waivers/deviations. All paperwork was submitted to the government for approval, which would allow Kollsman to deviate from the TDP. There was no response to the Kollsman requests, according to a Kollsman spokesman. "Nothing was implemented into Kollsman's product line unless it was approved by the government", says George Adamakos of Kollsman Inc.

When the "build to spec" contract for the AN/TAS-4C night sight was awarded to Kollsman, they were allowed to incorporate waivers/deviations into the night sight through the submission of requests to the government. The government allowed Kollsman to change the manufacturing process through sound engineering to meet government specifications. Even though Kollsman was a "build to print house" they were not allowed to deviate from the TDP without approval from the government.

Night Vision Laboratories was not experienced in rate production even through they did a very good job in research and development. The production contract awarded to Texas Instruments continued for some time before the production problems at Kollsman impaired the TOW-2 program. "The impact was severe" according to George Williams. The main issue was management of a production contract where the contractor had little or no integration and manufacturing technology experience. "The main problem, I believe, was having a government laboratory in charge of a production contract", Williams said.

"The Night Vision Laboratory did a good job in the R&D Program," says Coy Jackson, former chief engineer on the TOW system. George Williams, a former TOW Project Office, Deputy Project Managers says, "when I joined the TOW PM we were assuming the management of the program after the winner was announced of a multi-year contract. Reasons given for the selection of Kollsman was: very low price. " Kollsman was a build to print house, not a developer house. Thus they did not have the engineering knowledge or expertise that TI had", says Bob Nystrom, former NVL employee.

The program funding was always an issue. The TOW Project Office developed the TOW-2 system to meet the developing threat. The project often had to defend the TOW-2 decision over rival technologies that were being developed and pushed by government laboratories. This took

about two years to settle down. The project office continually went to the Department of the Army (DA) staff and explained the program. The DA staff would then cut the program funding and force the project office to continually defend its position. The project office estimate for the TOW-2 development was \$24M but the DA staff provided funding of \$18M. The program was executed at a value close to the \$24M estimated by the project office.

6. USER INVOLVMENT

The US Army Training and Doctrine Command (TRADOC) is an organization that is centrally managed for policy but decentralized in execution in different schools and centers through out the Army. The schools and centers monitor the development of new systems or the modification of existing systems to ensure that the soldier (user) requirements are met. Each major system has an appointed TRADOC System Manager (TSM) who compares operational requirements to hardware/software capability ensuring compatibility and integration into the Army. The school at Ft. Benning, Georgia was responsible for the integration of the TOW-2 system into the Army arsenal of weapons.

The operational requirements were specified in terms of the amount of armor to be penetrated and countermeasures to include infrared countermeasures and RF countermeasures. All were stated with a huge advantage attribute to the enemy. The operational specification of the amount of armor to be penetrated was always changing. However, the technical Specification of weight, stability, reliability, shelf life, etc was all stable during the TOW-2 system development to include the AN/TAS-4A night sight.

The key issues for the TOW Project Manager were (1) funding and funding instability as explained in the previous paragraph and (2) the development of the thermal (8 to 12 micron) beacon for the rear of the TOW-2 missile. Without this beacon the AN/TAS-4A, AN/TAS-4C and any subsequent versions would only have functioned as a night viewing devise and not a closed loop tracker. The thermal beacon being shuttered once a second allowed this loop to be closed.

IV. RESULTS OF TOW (TO INCLUDE AN/TAS-4A) USAGE IN OPERATION DESERT STORM

Approximately 70,000 TOW missiles were deployed to South West Asia for use during operation Desert Shield and Desert Storm. Of these, 1,426 missiles were expended during operations. There were 304 basic TOW missiles, 83 Improved TOW (ITOW) missiles, and 1,039 TOW-2 missiles expended.

While the effectiveness of the TOW system is measured in shot-to-kill ratio, the system aspects of performance must be considered. This means that the missile or night sight or day sight cannot be considered individually to determine total system success. However, there are some

comments from the soldiers that indicate how the AN/TAS-4A performed in battle and some of the shortcomings.

The US combat forces in South West Asia consisted of five heavy divisions, two light divisions, two armored cavalry regiments, and one Marine expeditionary force. The following TOW systems were employed in the ground campaign: the Improved TOW Vehicle (M901), the HMMWV (M966), the Bradley Fighting Vehicle (M2, M2A2) and the Cobra helicopter (AH1). The M2/M2A2 Bradley Fighting Vehicle was upgraded to the M3/M3A2 system. All ground systems maintained an equipment readiness rate of 90% or greater through out the entire ground campaign of the war. The Cobra helicopter TOW system maintained an average 80% readiness.

Some summary comments contained in after action reports from ground campaign forces were:

- "Marines report TOW-2A is a devastating weapon"
- "70%-75% shot-to-kill ratio"
- "All report-TOW-2A capable of destroying all armored vehicles encountered"
- "Troops praise both day and night sights"
- Some problems
 - "Night sight can't see thru heavy fog"
 - "Trouble looking into fires"
 - "AN/TAS-4A night vision sight roof mirror adhesive melted in high temperatures" (BFV)
 - "Gunnery complained of poor integrated sight unit picture resolution due to vibration chatter when vehicle is moving-Does not occur when vehicle is static" (BFV)
 - "Numerous crews reported the gun reticle in night sight mode can not be dimmed sufficiently and causes eye fatigue." (BFV)

All told, the single complaint most often regarding AN/TAS-4A performance was the effect from ground fires. These fires were from burning vehicles or oil wells.

CASE ANALYSIS

In summary, there are some important lessons learned from the development and integration of the AN/TAS-4A night sight in to the TOW-2 system. These lessons stem from some of the most difficult problems that the TOW Project Management Office faced during the AN/TAS-4A development and integration into the TOW-2 system.

- 1) The development and contracting for the delivery of the AN/TAS-4A was not totally centralized under the TOW Project Management Office. Decentralized execution of the effort without centralized management leads to several paths being pursued at the same time. The group ultimately responsible for the development and fielding of "the system" must integrate all efforts. These efforts may be government laboratories or contractor facilities. Today we have Integrated Product Teams (IPTs) but they are personality driven and not always effective. The "team" members must be empowered to make decisions that could affect the program.

- 2) A common vision at the beginning of the effort is imperative. All participating parties and the people working the effort must have a clear view of where the project is headed, what resources are needed to get to the conclusion and recognize when the effort reached the end state through a well defined exit criteria.
- 3) The TOW Project Management Office saw the lack of communication as the biggest problem in the development of the AN/TAS-4A. There were many participants including: the TOW Project Management Office, the Night Vision Electro Optics Laboratory, the Army Missile Command Research Development Engineering Center, Hughes Aircraft Company Texas Instruments, Kollsman, and Ft. Benning. All of them were not communicating in a positive manner and some appeared to have different agendas. Each had their own idea of how the program should be executed. Sharing information and communication is the cornerstone of success. This allows problems or issues to surface and solutions to be sought. Teamwork should become commonplace. Customer/user needs can be discussed to make sure that the operational needs are being met.
- 4) The selection of what appeared to be an unqualified second source for the AN/TAS-4A caused the TOW Project Management Office great concern and consumed considerable effort to prevent fielding issues. Had there been a better criteria for selection of the second source, other than cost, these problems could have been alleviated. Future system or component procurements must expand the criteria for contractor selection. Kollsman was a qualified source if one looks at the adherence to the governments TDP. Today Kollsman Inc. does have several contracts with the US Army Aviation and Missile Command for the production of night sight systems.
- 5) Overall the AN/TAS-4A and the TOW-2 program was a success. Bob Nystrom summed it up well, " Why was the AN/TAS-4A, rather than the MCTNS program, such a success? Because of a bunch of knowledgeable, hard working, dedicated people, both Government and contractor, conceived it, designed it, engineered it, and tested it. To accomplish this they sweated over it, cried over it, bled over it and even laughed over it."

CONCLUSION

The AN/TAS-4A development and fielding was an operational success even though the process was somewhat faulty. All of the problems and issues encountered and mentioned in this case study were overcome by a group of talented and dedicated individuals, both contractor and government, who wanted success. In many instances it was the management of organizations involved that cause the communication problems. The people doing the work knew what was needed and provided it. This is a good example of "let people who do the work-plan the work."

Appendix A

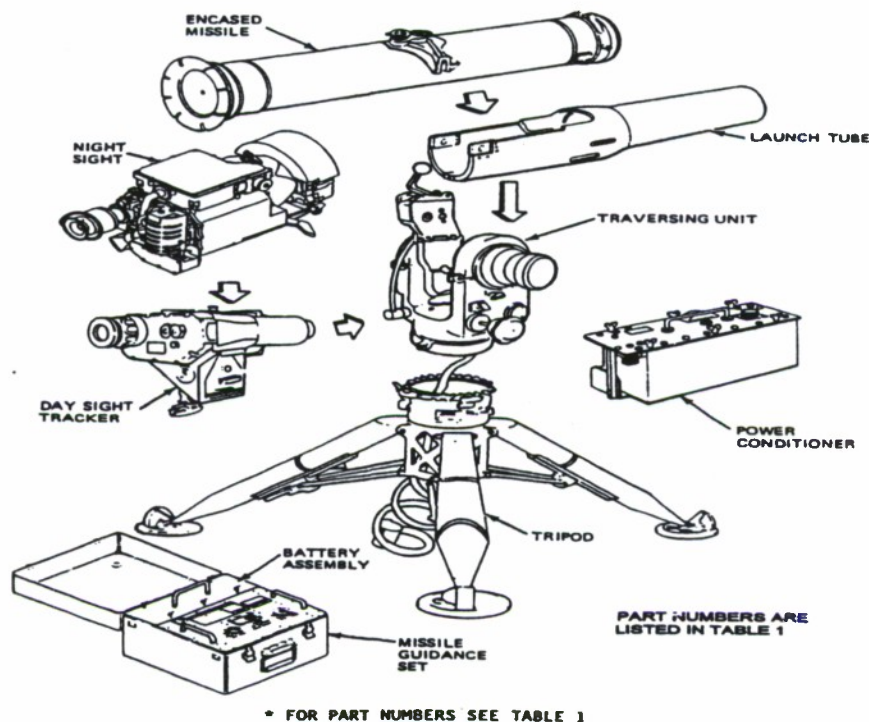
The tube launched, optically tracked wire guided (TOW) system is composed of several subsystems. Some of these subsystems will be discussed briefly only to show the relationship of components. System components and missile type will vary depending on the configuration i.e. ground, mobile or airborne systems. The TOW ground components are depicted in Figure 2.

A. Optical Sight. The visual telescope is the optical sight part of the day sight (optical sight/sensor). The TOW gunner can view targets through the visual telescope. The visual telescope is a high power (13X) folded telescope with a field of view of 5.5 degrees.

B. Day Sight Tracker: The day sight tracker sensor responds to and tracks the near-infrared radiation of the xenon beacon at the rear of the missile (all variants).

C. Night Sight: The AN/TAS-4 is a Forward Looking Infrared (FLIR) device. The night sight has a Galilean telescope with two fields of view (FOV). The wide field of view (WFOV), used for target acquisition, is 6.8 degrees by 3.4 degrees with 4X magnification. The narrow field of view (NFOV), used for target tracking and engagement, is 2.2 degrees by 1.1 degrees with 12X magnification. The night sight detects long wavelength infrared (IR) (7.5 to 11.6 microns) radiation (heat), also referred to as thermal emissions from the terrain and target, converts it to a video signal, and displays it for use in a gunners eyepiece. In the TOW 2 system, the electronically converted emissions are also sent to the Digital Missile Guidance Set (DMGS). The night sight is used as a secondary missile guidance unit, which may be automatically selected, by the DMGS computer, to guide the missile if the day sight tracker performance falls below a set threshold.

D. Missile: There were four versions of the TOW missile shipped to Southwest Asia (SWA) prior to Desert Storm. These were basic TOW missiles used for training, the Improved TOW (ITOW), TOW-2, and the TOW- 2A. The TOW-2 and TOW-2A missiles carry a thermal beacon to radiate long wave infrared energy (heat), which the night sight uses for tracking the missile. The thermal beacon is shuttered to distinguish it from other infrared sources.



The Ground TOW Launcher

Figure 2. Tow Ground Components

E. System Operation: The AN/TAS-4A and AN/TAS-4C night sights are mechanically attached to the day sight and electrically connected to the DMGS. The night sight is aligned (bore sighted) with the day sight telescope using the Bore sight Collimator (BSC) supplied as a part of the night sight equipment set. The night sight/day sight alignment is mandatory because the day sight tracker is always the primary tracking device, day or night. The TOW gunner can view the target with either the visual telescope (optical sight) in the day sight or with the infrared scanner display in the night sight. If visibility does not permit viewing with the day sight, the gunner must view with the night sight. The night sight converts long wavelength infrared radiation (heat) from the terrain and target to a visible display. In darkness, or during some daylight conditions of light rain, fog, or smoke the night sight provides a view of the target when the day sight will not. If and when the night sight is selected as the guidance unit by the MGS computer the gunner is not notified. After finding the target, the gunner must place the sight cross hairs on the target and hold them there while the missile is fired and automatically guided to the target. The TOW digital missile guidance set (DMGS) guides the missile along the line of sight via signals sent to the missile on wire spooled from the missile during flight. The signals are the difference between where the gunner is pointing the sight and the position of the missile as viewed by the optical tracker or night sight. The optical tracker tracks the xenon source and the night sight tracks the thermal source, both on the rear of the TOW missile.

F. Night Sight Configurations: There are several configurations of the TOW night sight. The night sights are the main component parts of Night Vision Sight Equipment Sets AN/UAS-12 with upgrade revisions A through D. The night sight consists of two main parts: The Afocal Cover Assembly is the outer protective housing that contains the infrared collecting optics and the FOV switching assembly; and the Basic Sight Assembly (BS) that contains the mechanical scanner, infrared focusing imager, the detector-Dewar assembly, the electronic processing circuitry, the power and control circuitry, and the visual display optical train. The significant revision differences are discussed herein.

AN/TAS-4: The AN/TAS-4 configuration is first or original night sight, which can be mechanically mounted, and bore sighted to a TOW day sight. The AN/TAS-4 is not electrically attached to the weapon system, therefore cannot provide guidance for the missile. The AN/TAS-4 uses a rechargeable coolant cartridge, commonly called bottle, to supply compressed air to cryogenically cool the detector to its operating temperature and a rechargeable nickel cadmium (NiCad) battery for electrical power. A fully charged bottle and battery will provide 2 hours of continuous night sight operation. Unlimited electrical power can be provided by using the Vehicle Power Conditioner (VPC), part of the equipment set.

AN/TAS-4A: The AN/TAS-4A configuration is the first major revision to the night sight to provide electrical input signals to the Digital Missile Guidance Set for use in missile guidance, especially for the TOW-2 system. The significant changes made for the A Revision were: A field of view (FOV) Switch activation mechanism was added to the Afocal cover assembly to notify the DMGS of the night sight field of view. The missile can only be fired with the night sight in the NFOV. A Post Amplifier Assembly (PAA) was added. This box is mechanically mounted to the top of the Afocal housing and provides an electrical interface between the basic sight and the TOW launcher. During this up-grade effort a previously scheduled Closed Cycle Cooler (CCC) modification was conveniently incorporated into the night sight, but was not a part of the up-grade. The electrical and mechanical changes to the basic sight are extensive. Electrical and optical alterations within the basic sight were made to enable the development of a Bore sight Pulse used for missile guidance. A FOV Switch was added to provide FOV information to the DMGS. New circuitry was added to provide signal outputs from the night sight preamplifiers to the PAA and also to provide power for and control of the CCC. A more sensitive detector-Dewar assembly was developed and installed. A Battery Power Conditioner (BPC) with new lithium batteries was added to the equipment set to provide 12 hours of back up power.

AN/TAS-4B: The AN/TAS-4B is same as the AN/TAS-4A. The only difference being the PAA is removed from the top of the night sight housing. The 4B configuration is used as the night sighting device for the Ground Locator/Laser Designator (GL/LD).

AN/TAS-4C: The AN/TAS-4C is an optically improved AN/TAS-4A. The significant optical enhancement changes made for the C Revision included, but not limited to optical stops added to the Afocal housing to eliminate unwanted stray or reflected IR radiation, all of the IR lenses, to include the detector-Dewar window, coatings were improved to promote greater signal transmission, and the IR reflecting surface of the scanner mirror surface was coated to promote

higher reflectivity of the IR radiation. As the C revision changes were a production cut in, the three enhanced common modules (scanner, IR imager, detector-Dewar) were mechanically keyed. This keying was done to prohibit the installation of non-enhanced modules into AN/TAS-4C or 4D models. However, the enhanced modules can be installed and used in AN/TAS-4A or 4B models. This allows for the propagation of the up-grade by attrition through the replacement spare parts.

AN/TAS-4D: The AN/TAS-4D configuration is the same as the AN/TAS-4C. The only difference, again, being the PAA is removed from the top of the night sight housing.

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Patriot PAC-2

Patriot Development Prior to PAC-2

Beginning in 1966, Defense Secretary Robert McNamara authorized the contract definition for the Surface-to-Air Missile Defense (SAM-D). In 1967, Raytheon was awarded the contract for the advanced development program. This four year program developed and demonstrated hardware elements and computer software which coordinated the operation of all elements performing the air defense functions from target detection through intercept. By 1970 the Track-via-Missile (TVM) guidance seeker was demonstrated by a series of real-time flight simulations. In mid-1970, Raytheon's contract was expanded to include an engineering development definition effort. The SAM-D engineering development program was initiated in 1972. The emphasis in this program was on the early initiation of missile flight tests. The advance development radar, computer and guidance hardware were modified to support guidance flight tests of the engineering development model missile. The engineering development model ground equipment was initiated in parallel development.

During the early part of the engineering development program, the tracking via missile concept was questioned by critics of this guidance system. These discussions reached Secretary of Defense Schlesinger who concluded that the importance and the cost of the program required that the guidance system be thoroughly proved before continuing the development program. Based on these discussions, the reoriented program, called Proof-of Principle, focused on the missile guidance system. In addition, in January 1974 Congress directed the Army to conduct a Cost and Operational Effectiveness Analysis (COEA) in coordination with the General Accounting Office (GAO).

The results of the COEA reaffirmed the need for an air defense system with SAM-D's capabilities. Initial testing conducted in 1974 verified SAM-D's on-board control system, aerodynamic and structural design of the missile, and in-flight acquisition and tracking by the ground based fire control group. In early 1975, in a test at White Sands Missile Range, SAM-D successfully destroyed a drone in its first engineering development test of the TVM guidance system. Subsequent tests proved that the TVM guidance system was robust against a variety of maneuvering targets and countermeasures. As a result of the performance in the Proof-of-Principle program, SAM-D was approved for return to full scale development in January 1976.

In 1976, with the resuming of full scale development, SAM-D was renamed Patriot. By 1977 an Army System Acquisition Review Council (ASARC) decision was made to accelerate the program. This decision moved the production date up from the original schedule of March 1983 to April 1980. This entailed the risk that the initial production equipment would not have the required operational reliability and software maturity. This decision resulted in the elimination of the third phase development tests and operational tests (DT/OT III). These tests were replaced with a production confirmatory test and a follow-on evaluation.

In September 1980, following the Defense Systems Acquisition Review Council III (DSARC III) production readiness review, low rate production for Patriot was approved subject to a verification test program. In October 1980, Raytheon began the initial low rate production that included five fire units and 155 missiles. This initial production was accompanied by a series of Follow On Evaluation (FOE) tests that

included operational software tests, testing of diagnostic software, retrofitting and testing of the missile, and checking reliability, availability, and maintainability (RAM). The final set of tests would be completed with the production equipment and with operational personnel. This test would be known as FOE-II. The first production units came off the line in early 1983. The operational tests began in June 1983 at White Sands Missile Range under the supervision of the Army Operational Test and Evaluation Agency (OTEA). FOE-II would be the first time combat troops would actually use Patriot in an operational environment. The tests would include search and track scenarios, simulated and live missile firings, including day and night operations.

FOE-II did not go well and the test results were substandard. There was excessive equipment downtime. Diagnostic and corrective action was complicated and led to delays in returning the equipment to an operational status. It became immediately clear that much of the equipment failure was due to production quality control deficiencies. As the tests continued problems multiplied, disagreements emerged regarding the design of the operational tests, and an adversarial relationship began to develop between Raytheon and OTEA. Before FOE-II was completed, OTEA made the decision to discontinue the operational testing. This turn of events was a shock to both Raytheon and the Patriot project office.

Following the discontinuation of FOE-II, Patriot was placed on what was labeled a "milestone schedule". The previous schedule for deployment to Europe was cancelled and Raytheon was instructed to systematically correct each problem that had been identified during the FOE-II tests. The milestone schedule meant that deployment and full rate production were postponed indefinitely. Only after a new Follow On Evaluation (FOE-III) would full rate production begin.

Lesson 1: A Corporate Culture that Responds to Adversity

Raytheon had been prepared to launch full rate production. With the failure of FOE-II, production capacity and staffing would not be utilized. Patriot was Raytheon's largest single program, and in 1983 it represented approximately 20 percent of the company's total sales revenue. Both Raytheon corporate management and the engineers in the Missile Systems Division knew that Patriot would either be deployed or cancelled based on the success of the impending FOE-III testing.

What transpired next can only be described as a massive corporate response to the challenge that entailed extraordinary effort on the part of Raytheon's Missile Systems Division. Engineers scrutinized every aspect of the FOE-II test results in an effort to identify every potential problem source and take corrective action. A concerted effort was mounted to improve software diagnostics. Sensors were added to the system so that operators could detect faults more readily. The technical manuals were rewritten based on the Patriot project office guidance on specific procedures. Raytheon corporate management brought in William Swanson, a very talented production manager, to turn around the Andover, Massachusetts production facility. Swanson overhauled the entire quality control system and vastly improved production quality.

Steve Stanvick, the Patriot chief engineer at Raytheon, was placed in charge of the FOE-III preparation. Stanvick realized that the existing organization within the Missile Systems Division resulted in diffused responsibility. To correct this problem, he created a temporary organizational structure in which engineers were grouped into ad hoc

teams with a single technical manager over each major area. John Kelley, the manager of flight tests, observed that many of the technical professionals were routinely working 60 hour weeks during this period. Levels of exhaustion were high, but the relentless effort to correct each problem in preparation for FOE-III continued on its compressed schedule.

In July 1984 FOE-III was initiated. The tests were extraordinarily successful. Patriot surpassed all the acceptable target values, and in some cases by margins in excess of 50 percent. During the tests the system was operational over 90 percent of the time. The missile flight tests achieved a 100 percent rating by OTEA and the testing was completed ahead of schedule in September 1984. Immediately following the successful FOE-III tests, the decision was made to ramp up production and begin the deployment of Patriot in Europe.

The corrective action system that was instituted resulted in impressive improvements in a period of less than one year. This structured response to the FOE-II crisis literally reshaped the company's approach to the transition from development to production for the future. This would turn out to be important as the program moved into PAC-1, and historically significant, during the accelerated transition to production for the PAC-2 Gulf War deployment. It is to Raytheon's credit that the firm possessed the corporate culture that embraced such a radical turnaround.

Lesson 2: The Tactical Missile Threat and Obtaining Support for PAC-1 and PAC-2

The original requirements for Patriot (SAM-D) included an anti-tactical ballistic missile capability. However, this requirement had been eliminated by TRADOC (the Air Defense Command) early in the program. The program prior to the start of full rate production in 1984 focused exclusively on the anti-aircraft requirement. The issue of the added anti-tactical missile capability had encountered some resistance from the beginning within TRADOC. The reasons were varied, but included the issues of cost, schedule and technical difficulty. In this regard, in order to achieve the anti-aircraft capability, the technical development effort was so significant that the consensus between TRADOC and the Patriot project office was to focus resources on this critical task. To attempt to achieve both objectives from the beginning would diffuse resources and inevitably prolong the development schedule. A second counter-argument that was generally accepted by TRADOC was that tactical missiles were inherently inaccurate, and therefore, posed a lesser threat to military targets. As events unfolded in 1990 and 1991, however, the fallacy in this argument would become extremely clear because of their potential as a weapon of terror against civilian populations.

In any case, by 1985 Patriot was progressing in high rate production, and Colonel Lawrence Capps replaced Brigadier General Donald Infante as project manager of the Patriot project office. With production under way, the timing was right to shift attention to the tactical missile threat. The specific threat was the Soviet SS-21, and this became Colonel Capps primary objective. Achieving the anti-tactical missile capability would require resources, and TRADOC (the Air Defense Command) was ambivalent. However, Colonel Capps persisted in successfully convincing the Office of the Secretary of Defense to allocate budgetary resources to the program (i.e., OSD directed funds). During this same timeframe the Patriot project office succeeded in negotiating a multiyear production contract (five year contract) with Raytheon. This was an important

development because it provided the level of funding stability that would be required to keep the anti-tactical missile program on track.

Initial efforts were called Patriot Anti-tactical Missile Capability-1 (PAC-1), which involved software changes to reshape the radar search pattern and to reshape the missile trajectory. The test results were promising, but it was clear that changes were needed to the warhead and fuze to make the system more effective. However, it was apparent that these measures would still not be sufficient to gain the increase in the guidance accuracy needed. Thus, in order to increase both political and budgetary support, the Germans were approached regarding a joint program. The Germans communicated a high level of interest. They were already acquiring Patriot missiles and the anti-tactical missile capability was attractive to them. In 1986, the Germans agreed to fund 40 percent of a program for an experimental new seeker called the multi-mode seeker. This 60/40 split was sufficient to fund a phased effort that was to test the seeker in hardware-in-loop ground simulation tests, and then incorporate it into the missile and conduct flight tests. However, this new missile seeker was destined never to reach production, as events would drive the schedule into rapid production of the existing PAC-2 design.

The PAC-1 and PAC-2 Programs Proceed on Schedule and Within Budget

The first phase of the advanced capability program, PAC-1, involved software modifications to the Patriot ground equipment and improved guidance and control. These software changes would allow the Patriot missile to essentially fly up the reverse trajectory of an incoming SS-21 missile. The PAC-1 software changes allowed the radar to orient into a high altitude search mode for surveillance tracking and launch against the inbound missile. In April 1985 Raytheon completed the system definition effort for the PAC-1 ATM software modifications. The PAC-1 software development contract was awarded to Raytheon in June 1985. By July 1986 the software changes had been completed and validated. In a test at White Sands Missile Range in September 1986, a Patriot missile successfully intercepted a Lance missile similar to the Soviet SS-21. Following the testing, the PAC-1 capability was deployed with the release of the Post Deployment Software Build #2 in July, 1998.

The second phase of the advanced capability program, PAC-2, involved missile modifications including the fuze, warhead, software modifications, and new guidance algorithms. The PAC-2 program provided Patriot with catastrophic kill capability against longer range, INF treaty compliant missiles such as the Soviet SS-23. The modifications to the warhead included larger hardened steel fragments that would be released following detonation of almost 100 pounds of high explosive. This improvement was necessary in order to penetrate the shell surrounding the TBM's warhead. The fuze, developed by the Harry Diamond Labs and Bendix Corporation, had a faster reaction time that was necessary for high closing speed engagements.

The Patriot system consisted of a ground radar, an engagement control station, an antenna, an electric power plant, and typically eight launchers per fire unit. Each launcher contained four missiles in its individual storage, transportation, and launch containers. The radar was a multifunctional phased arrayed radar which performed a variety of surveillance, acquisition, and guidance tasks in directing a battery of launchers. With multiple guidance modes, the system had the capability to switch modes to adjust to

enemy electronic counter measures. The missile was 17.4 feet in length and was powered by a solid propellant rocket motor that approached mach 3 speeds. The missile itself weighed 2200 pounds and had a range of 43 miles. A picture of the PAC-2 system is presented in Figure 1.

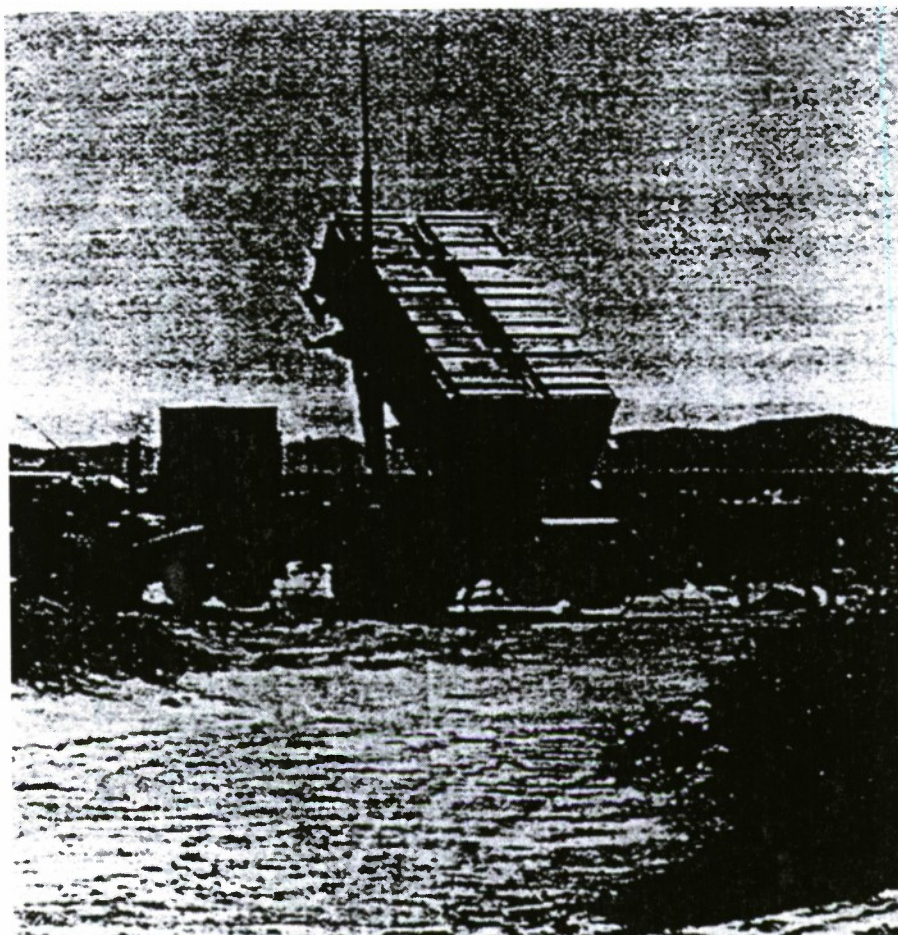


Figure 1 – PATRIOT PAC-2

PAC-2 development proceeded through 1986, 1987, and 1988. In addition to the work on the fuze and the warhead, software development proceeded on incorporating the pulse doppler search/track capability. Additional preplanned product improvements during this timeframe included the clutter canceller modification, integration of the modular azimuth and positioning system with Patriot, the standoff-jammer counter, and improvements to reliability, availability, and maintainability.

The testing program included component level, subsystem level, and system level testing. Extensive software testing included stand alone tests and hardware in the loop tests. The warhead testing verified its spray pattern, fragment velocity, and fragment ruggedness. The fuze underwent testing to verify its performance on a variety of targets with different trajectory geometries and closing velocities. With the success of the test

program, by December 1988, the Army In-Process Review (IPR) approved production for PAC-2.

The PAC-2 production run began in February 1989. The guidance section was built by Raytheon in Andover, Massachusetts. The propulsion section was produced by Morton Thiokol at Redstone Arsenal. The final assembly was completed by Martin Marietta in Orlando. Given the long lead-time on production, the first PAC-2 missiles were scheduled to be fielded in early 1991.

Lesson 3: PAC-2 Schedule and Cost Performance Can Be Attributed to Sound Acquisition Strategy, Technological Readiness, and Effective Project Management

One important factor that contributed to the PAC-2 schedule and cost performance was a sound acquisition strategy. Following initial development, the first Patriot production contract was awarded on a cost plus incentive fee/award fee basis. This type of contract was selected by design in order to distribute risk at a level acceptable to both the contractor and the government. As the Patriot system matured, and cost and technological uncertainty decreased, cost type contracts began to be partially replaced by fixed price incentive and in some instances, firm fixed price contracts. On a proportional basis, this placed increased monetary risk on Raytheon and the subcontractors relative to the government. However, with risk being reduced as a result of technological readiness and production knowledge, this was acceptable to Raytheon and the subcontractors.

In March 1987, a multiyear production contract was awarded to Raytheon. This five year contract allowed Raytheon and the subcontractors to lower costs through economies of scale in lot purchasing, efficient utilization of facilities, and reduction in contract administration costs. While PAC-2 did not transition into production until 1989, the primary effect of this multiyear contract on PAC-2 was the overall funding stability that it provided. Retired Brigadier General Capps observed that this funding stability for the Patriot program was important in keeping PAC-2 development on schedule. The PAC-2 program could be injected into the ongoing production program by cutting in engineering change proposals rather than starting an entirely new production line. This approach resulted in maximum efficiency.

While incentive fees were commonly utilized with the development contracts, the most critical incentive was the continuation of the large production contracts. Therefore, by creating incremental project milestones for design and testing during engineering development, the financially lucrative production contract could be obtained by successfully achieving each of the sequential milestones.

The technological readiness level, or maturity, was also a factor that contributed to PAC-2 schedule and cost performance. A.Q. Oldacre, the deputy project manager for the Patriot project office during PAC-2, observed that because work on Patriot had been progressing at Raytheon since 1967, Raytheon had built a large base of pertinent technical knowledge. In the Raytheon laboratories, knowledge of the basic technologies such as phased array radar, guidance and control, and software had reached a high level by the time of the inception of PAC-1 and PAC-2.

Similarly, in the Army laboratories a large base of technical knowledge had developed over the same timeframe. For example, in the Research, Development, and Engineering Center (RDEC) at Army Missile Command (MICOM), the Software

Engineering Directorate managed the Patriot software verification and validation program in cooperation with the Patriot project office. The RDEC Guidance and Control Directorate assisted with hardware validation and developed simulations for Patriot jointly with Raytheon. The PAC-2 fuze was developed with Harry Diamond Labs, and RDEC at MICOM assisted in fuze testing. In addition, Aberdeen conducted the PAC-2 warhead testing. This extensive base of expertise in the government laboratories and test facilities contributed to the high technological readiness level that facilitated PAC-2 development schedule performance.

Effective project management also contributed significantly to the PAC-2 schedule and cost performance. The government project office utilized a functional structure with a program management office that included an acquisition management branch, a cost estimating/budget branch, and a cost/schedule control branch. There was a production/configuration management office, a hardware engineering division, a software engineering division, a product assurance division, and a systems engineering division. In addition, there was an office for Patriot support that included deployment management, logistics management, and a Patriot readiness center. The project office also included a project counsel legal office, an administrative office, and liaison offices for Germany, Japan, and the Netherlands.

At Raytheon, the Patriot program office within the Missile Systems Division included personnel who would interface with the government counterpart in the various functional areas. The program office contained a large technical staff. Raytheon utilized a laboratory structure where engineers in the Bedford system design lab, systems engineering lab, software engineering lab, test lab, and so forth, were in a matrix organization with the program office functional areas. This system worked effectively for several reasons. First, during the PAC-2 timeframe Raytheon retained a large technical staff in the program office itself. These individuals, for the most part, had extensive Patriot experience in their respective areas of specialization. Secondly, there was significant technical depth in the Bedford labs in each area that pertained to the Patriot system. Third, the coordination within this matrix system in terms of task assignments was managed effectively. Finally, the interface between the Raytheon program office, the subcontractors, and the government Patriot project office was effectively managed.

PAC-2 development occurred in an era before integrated product teams began to be used widely. However, temporary or informal modes of cross organizational integration were implemented which had some similar characteristics to integrated product teams. Larry Moore, Patriot project office technical director, observed this occurring in the software engineering area with the creation of teams that included Raytheon personnel, project office personnel, and the contractor or Software Engineering Directorate personnel involved in validation. However, Moore also observed that structural modes of integration (like cross functional or cross organizational teams) are only effective to the degree that the individuals involved have the requisite level of technical knowledge and to the degree that those individuals are striving to work cooperatively. In the absence of cooperation and requisite technical expertise, structural modes of coordination are ineffective. A.Q. Oldacre, the deputy project manager during PAC-2, noted that the level of cooperation and the openness regarding disclosure of problems was such that coordination between Raytheon and the project office was extremely effective.

When PAC-2 entered production, the effectiveness of this coordination was facilitated by the fact that the Patriot project office had a team of engineers on site at the Raytheon Andover manufacturing facility as liaisons. Furthermore, internal coordination at Raytheon had improved significantly over the initial production runs. To facilitate the transition to production, engineers that were involved in R&D design work served in an advisory capacity during the transition to production. Similarly, production engineers at Raytheon provided input into design decisions at earlier stages in order to insure design for manufacturability. This was a clear case of organizational learning. In the initial production runs this type of integration, that is characteristic of concurrent engineering, was not in place. By 1989, when the PAC-2 changes and the other preplanned product improvement changes were moving into production, integration had been improved significantly. These factors demonstrate the high production readiness level at Raytheon that also contributed to schedule and cost performance.

Lesson 4: In War, One Must Learn to Expect the Unexpected

On August 2, 1990, Saddam Hussein launched the Iraqi invasion of Kuwait. At this point in time the PAC-2 missiles were in the production build-up cycle with the first missiles scheduled to come off the production line in approximately five months. Only three PAC-2 R&D missiles were in the inventory in August 1990, and these had been scheduled for use in operational testing. While the development testing had been completed, there was still operational testing that remained to be conducted.

The intelligence reports coming back from the Middle East immediately communicated the nature and the extent of the Iraqi missile threat. The missile was the Soviet built Scud. However, PAC-2 had been designed to counter the SS-21 and SS-23 threats. The Scud had been discounted because it was an older system that the Soviets had replaced with their more modern systems. The Soviets had sold their aging fleet of Scud missiles to their third-world allies, and Iraq was preparing to use this weapon against the US forces and our Coalition allies. To make matters worse, the Iraqi Scuds had the capability of delivering both conventional and chemical warheads. Furthermore, the Iraqis had modified the propulsion section so that the Scuds range was capable of reaching the population centers of Israel. As if the situation could not be any worse, the Iraqi propulsion modifications also resulted in higher velocities than the SS-21 or SS-23. Hence, the modified Scud Al-Hussein reached velocities of 6,500 to 7,200 feet per second. The Soviet missiles the PAC-2 had been designed to intercept reached velocities between 5,200 and 5,900 feet per second. As Herb Sanborn, Raytheon Patriot systems engineering manager, observed, "in war, one must learn to expect the unexpected".

In the first week of August 1990, what was unfolding was nothing less than an engineering and production challenge of historic proportions. Not since 1944 had an American defense firm and a government project office been faced with a challenge of this magnitude. Colonel Bruce Garnett, the Patriot Project Manager, was summoned to Washington where he was asked to present the simulation data that had been developed by RDEC at MICOM and Raytheon. Upon reviewing the information the Army Chief of Staff, and subsequently General Colin Powell, made the decision to deploy PAC-2 in the Persian Gulf. The Program Executive Officer, BG Robert Drolet, directed an emergency early release of Post Deployment Build-3 (PDB-3) with necessary software

modifications, and parallel final tests to assure that adaptations for the Iraqi Scud worked properly.

What transpired next could only be described as an extraordinary acceleration of effort. A.Q. Oldacre, the deputy project manager, without any formal contract, on a phone call alone, instructed the Raytheon program office to accelerate production as rapidly as possible. Raytheon immediately moved into 24 hour, 7 day per week, full plant capacity production. Simultaneously, Larry Moore and Don Adams at the Patriot project office in Huntsville, in cooperation with Raytheon, initiated the effort to make the necessary software modifications to counter the Scud threat. The software engineers at Raytheon immediately realized what the challenge entailed and moved into a mode of extraordinary effort. In order to make the necessary software modifications and conduct the validation testing, it was reported that software engineers at Raytheon were working 16 hour days. For Walt Trainor at Raytheon, and A.Q. Oldacre at the Patriot project office, this effort would be their greatest challenge.

While this was occurring, the German PAC-2 production line also transitioned to full capacity. In coordinating production, it soon became apparent the production of the new warheads in the U.S. was roughly two months behind the German contractor, MBB, as a result of a labor strike. Consequently, the Patriot project office coordinated a transfer of German built warhead parts to the U.S. for assembly. As a result, daily deliveries of parts were shipped from the MBB plant in Bavaria to Ramstein, then on to Dover Air Force Base in Delaware, then to East Camden, Arkansas for warhead subassembly, and finally, to Orlando for final missile assembly.

By January 1991, 424 PAC-2 missiles had been shipped to the Persian Gulf. However, it was unclear if this would be sufficient as intelligence data revealed the magnitude of the Iraqi Scud threat. By this time warhead production in Arkansas, guidance section production at Raytheon in Massachusetts, and fuze production in Baltimore were exceeding the final assembly capacity of Martin-Marietta in Orlando. As a consequence, the Patriot project office shifted its focus to converting PAC-1 missiles in the inventory into PAC-2's. This assembly process involved changing the warhead, fuze, software, and other changes to a number of the existing missiles in the inventory. The missile forebody was sent to Raytheon for the replacement of components, then a second final assembly facility was brought on line at Red River Army Depot, and a third was brought on line in Germany. Running parallel assembly operations resulted in a significant increase in the number of missiles being shipped to the Persian Gulf as hostilities erupted in January 1991.

Lesson 5: The Primary Challenge for the Project Managers: Agility in Adjusting Rapidly to Changing Requirements and Accelerating Production

Several important factors contributed to the ability of Raytheon and the Patriot project office to exhibit such extraordinary organizational agility in adjusting rapidly to the changed requirements and the need to accelerate PAC-2 production. A.Q. Oldacre and Larry Moore from the Patriot project office, and Herb Sanborn from Raytheon considered stability and continuity in staffing to be an important contributing factor. This was important particularly in the effort to rapidly modify and test the software to allow for the interception of Scud missiles. Many of the key technical people at both Raytheon and the government project office had worked on the program for over 10 years. This

depth of experience that was system specific proved to be critical when the rapid changes were required. In large complex projects learning curves should not be underestimated. While there is an advantage to some degree of movement of technical personnel to transfer knowledge and ideas from other projects, this can reach a suboptimal level. What is needed is a core of highly talented individuals with extensive system specific or domain specific knowledge. This was critical, particularly in areas like software, and this contributed significantly to the ability to adjust so rapidly.

The dramatic acceleration of production was made possible by several important factors. First, the Army had the foresight to contract with Raytheon (and the subcontractors) to develop the tooling and production facilities so that the capacity would be in place in the event of war. A second contributing factor was the level of training and expertise of Raytheon production personnel. This had the effect of insuring quality as production ramped up to 24 hour, 7 day schedules at full plant capacity. Another factor that affected quality was the numerous quality control initiatives implemented by the production manager, Bill Swanson, during the period between FOE II and FOE-III. The changes that were implemented during that timeframe paid very real dividends as production accelerated in preparation for war. Finally, the Patriot project office had the foresight to insure multiple production sources of critical components. Thus, when Chamberlain was seriously behind schedule on warhead production, the adjustment could be made to procure the warheads from MBB in Germany. Similarly, parallel production could be brought on line when the effort shifted to transforming a number of existing missiles to PAC-2 missiles.

General Larry Capps observed one other factor that allowed for the extraordinary acceleration in production. This was the restricted level of breakout. During the mid 1980's there had been an effort on the part of the Department of the Army to increase the level of breakout, or the level and number of subcontractor production contracts, on numerous programs. The logic of this strategy was to reduce costs through increased competition. In the case of Patriot, this effort was carefully managed by the project office, and breakout was actually relatively restricted as a result. This proved to be providential because when Patriot production had to be accelerated to meet the requirements of the Gulf War, a larger network of suppliers would have inevitably slowed production due to the complexities and inevitable uncertainties of coordination.

Another important factor that contributed to the ability to rapidly shift the systems' guidance from aircraft, SS-21 and SS-23 missiles to Scud missiles, was the fact that Patriot was designed to be extremely robust. As Herb Sanborn observed, in order to be prepared for unexpected eventualities, a missile with multiple guidance modes (to avoid electronic countermeasures), and the capability to modify guidance algorithms as well as other ground software in a short period of time, allows for greater versatility.

There was one more factor that contributed to the dramatic acceleration in production and the rapid implementation of software changes. This can perhaps be described as a cultural characteristic that Americans seem to possess. It is an extraordinary ability to rise to challenges and exhibit extreme levels of motivation in the face of a national crisis. A. Q. Oldacre described it in this way: "I have often wondered whether or not this country could still do things like it did in World War II. I know now that it can. If we turn it on, and ask our industry and our people to do things like we did in World War II, there is no doubt in my mind that we could do it again".

PAC-2 Plays a Critical Role in the Gulf War

The United States and Coalition forces launched the massive air attack on Iraq on January 17, 1991. On January 18, Iraq initiated use of its weapon of terror by launching Scud missile attacks on military targets and civilian populations. Due to the tremendous production acceleration that had been occurring since August, there were over 400 Patriot PAC-2 missiles in the Persian Gulf by this date. Patriot units immediately went into action to counter the threat. This would be the first time in history that tactical ballistic missiles would be used in hostile wartime attacks on civilian populations. This would also be the first time in history that these attacks would be countered with an anti-tactical ballistic missile.

As the war progressed, software adjustments were made to respond to observations from combat. Because the Scud missile tended to breakup during the final phase of its trajectory (re-entry into the atmosphere), multiple targets would appear on the radar screen. Engagement operations were modified to reduce undesirable engagements. Raytheon and Patriot project office personnel worked rapidly to make further adjustments to reduce tracking and engagement of false targets (targets that were not incoming warheads). Other forms of radar interference (i.e., backload reflection) were discovered and rapidly corrected by Raytheon engineers in Saudi Arabia and Massachusetts as the Scud attacks proceeded. By February 28, 1991, estimates of successful interception ranged as high as 70 percent in Saudi Arabia and 40 percent in Israel.

There was some controversy over the question of exactly how many of the 159 Patriot missiles launched during the conflict actually intercepted their targets. Part of the controversy can be attributed to reporting deficiencies. Performance assessments were also subject to differing definitions. For example, if a Scud missile was approaching an airbase, and the Patriot did not destroy the warhead but did divert its path so that the warhead landed in the desert, some defined this as a successful intercept. Others defined this as a failed intercept. Another issue was the difference between the performance in Saudi Arabia and Israel. In large part, this could be explained by the differences in training levels between U.S. and Israeli units, differences in engagement control, and the fact that it was used to defend large geographic urban areas in Israel versus small geographic area military bases in Saudi Arabia.

Regardless of any controversy regarding the number of Scuds that were destroyed, disabled or diverted, the fact remains, Patriot saved many lives, both civilian and military. For an incremental development investment under \$150 million, the PAC-1 and PAC-2 programs enabled the Patriot air defense system to be upgraded from anti-aircraft to anti-tactical ballistic missile capability. This achievement made the Patriot PAC-2 one of the most cost effective defense systems in the U.S. inventory.

Perhaps the most important contribution made by PAC-2 in the Gulf War was its critical role in holding the fragile multinational Coalition together. The historical significance of this role has been underestimated. Patriot was the only defense against the Scud attacks on Israel. When Saddam Hussein began launching Scud missiles at the major population centers in Israel the pressures mounted for Israel to be drawn into the conflict. Had this occurred, the likelihood of the Coalition unraveling would have been extremely high. With such a chain of events, and in light of the chemical, biological, and

nuclear capabilities in the region, one can only speculate as to where the escalation would have ended.

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Endnote

¹ This case utilized interviews from some of the same respondents as the Fenstermacher reference. However, the issues examined in this case study focus on PAC-2 development and vary significantly from the reference noted above so as to warrant a separate case study.

M
TADS/PNVS

**TARGET ACQUISITION DESIGNATION SYSTEM/PILOT NIGHT VISION
SYSTEM (TADS/PNVS)**

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1. Background

The first shots of Operation Desert Storm were fired by AH-64A Apache Helicopters (Task Force Normandy) on January 17, 1991. The TADS/PNVS was used to acquire the targets. At first, these systems used the heat from the target to guide the missiles. When a flash was distracting some missiles, the pilots switched to optical guidance. The targets, two state-of-the-art Soviet-built radar sites, which threatened to give early warning of the initiation of the air campaign, were simultaneously attacked at 2:38 A.M. The targets were completely destroyed. This allowed the allies to fly surreptitiously right in and bomb Iraq.

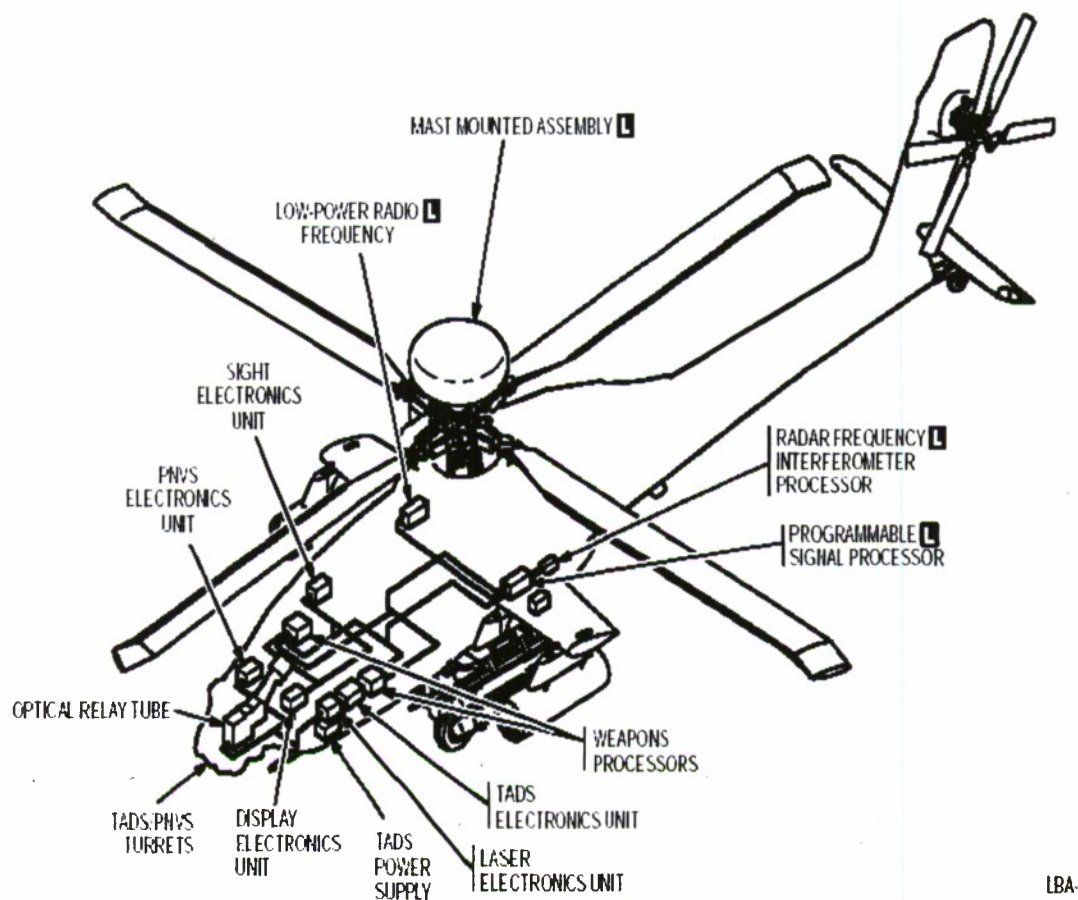


Figure 4-1. Sight Subsystem

Figure 1 – TADS/PNVS on APACHE (Longbow Configuration); from TM-1-1520-251-10, Operator's Manual for Helicopter, Attack, AH-64D, Dec 1998

The Target Acquisition Designation System / Pilot Night Vision System (TADS/PNVS) was conceived by The U.S. Army Missile Command (MICOM), which initially led the developmental effort, as a target finding sensor for the HELLFIRE semi-active laser guided missile. The TADS/PNVS program was subsequently transitioned to the Apache Attack Helicopter Program Management Office (AAH PMO). TADS/PNVS was developed in the 1970s and 1980s under control of the TADS Program Office, which was a part of the AAH PMO.

Developing a system such as TADS/PNVS requires accomplishing a number of complex, interrelated tasks. This work was accomplished successfully and the system was relatively when it entered the transition to production phase. However, still more work had to be done to support successful production, both during the transition to production and in the early stages of production. Engineering changes required included those to improve pointing angle accuracy, to achieve a noise-free infrared sensor, and to obtain consistency of Line-of-Sight Stabilization (which required repeated changes). The required delivery rates of 10, and then 12 per month, ramping up from one per month, increased the level of difficulty.

In transitioning to production, the system experienced a relatively short delay of less than six months. As noted, there were some minor changes during transition to production, in order for the system to meet or improve performance. Similarly, there were some minor changes to the system while in production, mostly to increase system reliability. The contractor had a financial incentive to improve reliability (which eventually saves the Government money also.) Some changes were also required due to parts becoming obsolete.

There was a significant increase in development costs. The original TADS/PNVS contract was for \$45 million, and it ended up costing twice that amount. However, the system met or exceeded technical performance goals. The system was deployed on the AH-64A Apache Helicopter, and, as described, performed effectively in Operation Desert Storm.

The timeline that follows in Table 1 was compiled by merging dates obtained from respondents with data from other TADS documents (From Hot Air to Hellfire, Selected Acquisition Report (SAR), and Test Plan for TADS/PNVS Competitive Development).

Date	Event
22 June 1973	Competitive Phase I, Development Contracts awarded to Hughes Helicopters and Bell Helicopters Textron, Inc
1976	Systems Planning
7 Dec 1976	DSARC approved AAH entry into full scale development (Phase II) and Secretary of the Army selected Hughes Helicopters, Model YAH-64
10 Dec 1976:	Down select to Hughes YAH-64A
10 Mar 1977	TADS/PNVS directed for development, contracts awarded to Martin Marietta and Northrop Corporation.
1977	Development Start
1 Dec 1979 to 29 Feb 1980	The TADS/PNVS competitive development test was conducted at Yuma Proving Grounds (YPG). It was a fly-off between the Martin Marietta Corporation and Northrop Corporation TADS/PNVS advanced prototypes, each mounted on AH-64 aircraft.
1980	Transition to Production
30 Jan 1981	Army awarded Long Lead Time contract to MMOA (TADS/PNVS)
20 Feb 1981	Army LLTI contract to Hughes (AH-64)
Jun-Aug 1981	Operational Test (OT II) was completed on time at Ft. Hunter-Liggett
18 Nov 1981	Army System Acquisition Review Council (ASARC) III was completed
FY 1982	Congress approves LRIP, \$444.5 M Contract for 11 aircraft
26 Mar 1982	DSARC III held, initial production of Apaches approved
April 1982	Production contracts awarded to Hughes, Martin Marietta-Orlando, and General Electric (engines)
Early 1984	McDonnell Douglas acquired Hughes Helicopter
26 Jan 1984	McDonnell Douglas Helicopter Company (MDHC) first production aircraft (PV01) rolled out
22 July 1986	Initial Operational Capability

Table 1. Overall Program Timeline

2. Technology Readiness?

The three critical technologies of the TADS/PNVS were: Laser to sensor bore-sight (LSBS), Line-of-Sight Stabilization (LOSS), and Forward-looking Infra Red (FLIR) Target Acquisition (FTA). The critical technologies were used as originally planned. All three of the technologies were essential; TADS would not have worked without them. LOS Stabilization was included in early development, FTA in later development. Bore sighting wasn't finalized until early production – a lot of time was needed, but not all that much money. Although the technologies were immature at the beginning of development

(none had been demonstrated in a prototype system in a relevant environment), the development phase was successfully completed and the system was eventually accepted for full production.

When system planning and pre-development began, two of the three critical technologies (Line-of-Sight Stabilization and FLIR target acquisition) had been verified in breadboard form in a laboratory environment. LOSS had never been tried on a helicopter – a high-vibration environment. The third technology (Laser to sensor bore-sight (LSBS)) had only been verified by a combination of laboratory work and analytical studies. Three groups did most of the early technical work: the MICOM Guidance and Control (G&C) lab, the US Army Night Vision Lab (NVL), and Martin Marietta-Orlando's science and technology group. Additionally, Frankfort Arsenal gave support in fire control and optics.

By the time the system was in development, laser to sensor bore-sight had been verified completely in a laboratory environment, and the other two technologies had been verified in a realistic, though simulated, environment. Said another way, these technologies were advanced enough for the development phase to start, but not yet ready for fielding. A prototype had been developed, and the system met the specification, though not consistently. The Army science and technology organizations mentioned previously contributed to development by providing engineering support, simulation, and requirements interpretation.

When the system was ready to transition to production, the technologies were considerably more advanced. An actual system had been tested, and the laser to sensor bore-sight had been qualified in test and demonstration. The technology was proven in its final form. The other two technologies, in final form, had also been successfully tested in a realistic operational environment. At this point the system was given the go-ahead for production.

There were still some production reliability and manufacturability issues to work out, but the essential system was ready. Bore-sight stability is affected by a number of characteristics of all sensors, bore-sighting components, and the characteristics of the stabilized turret. This made doing the bore-sight design difficult until after the rest of the TADS system has been designed, built and tested. During this phase, Martin Marietta did the primary work. The PMO oversaw this effort, and MICOM G&C, NVL, and Frankfort Arsenal provided support.

This additional work effort carried over into the transition to production, and in early production, but the reward was that they were at a fairly good level of readiness. Operational Testing was completed on time at Fort Hunter-Liggett in June-August 1981. Changes to the system were critical, to meet or improve performance, to increase system reliability and to improve reliability, but did not delay system production very much. The TADS/PNVS contract cost twice the amount originally contracted, from \$45 million to about \$90 million; but the system met its technical objectives and performed well in Operation Desert Storm.

3. Role of Government S&T organization?

The U.S. Army Night Vision Lab (NVL) was the original developer of the FLIR technology used in the TADS night sight and the PNVs. Technical staff members provided support to the TADS/PNVs program from the very start of the system planning phase, and they continued to provide support through development and the transition to production phase.

The MICOM Guidance and Control (G&C) Lab was involved in system requirements for Total Pointing Error (TPE) for the laser designator, which is a component of laser to sensor bore-sight. G&C labs did a lot of testing and simulation work to develop these requirements and early work on the laser hardware.

Martin Marietta Corporation's science and technology organizations also did their own work in response to the anticipated requirement for the ASH and AAH programs. They invested research and development resources to develop the technology and to create a manufacturing plan.

In addition to the involvement listed above, Frankfort Arsenal, as well as U.S. Army Night Vision Labs (NVL) and MICOM Guidance and Control (G&C) Lab, gave significant support in fire control and optics in developing requirements, evaluating proposals and monitoring development progress. These labs were quite open to requirements changes and other project ideas.

Army labs contributed to readiness at the start of the planning phase for FLIR target acquisition. They continued to provide readiness support for the three critical technologies throughout development and the transition to production phases.

4. Difficulties in integrating technology?

The contractor had to make serious changes in their production process for two of the three most critical technologies (LOSS and FLIR Target Acquisition) and significant changes for the third (Laser to sensor bore-sight). The contractor, Martin-Marietta, was not then producing similar systems. Components were similar, but new types of system tests had to be developed in order to guarantee meeting system specifications.

Using a novel testing philosophy to find system faults earlier, some requirements were flowed down to lower level modules and components to eliminate failures earlier in the process. These tests were often unique because they were driven by system-level requirements.

TADS / PNVs was a critical contract for Martin-Marietta, and its upper management treated it as a high priority. They provided personnel in adequate numbers with the skills needed for the project. Some specialties were from functional groups that gave the TADS/PNVs group a high priority, but didn't transfer personnel – because their full time services were not necessary.

Various risk factors caused the program major difficulties. For example, taking the risk out of the new technologies was a major effort. Also, significant effort was

needed both to scale the technology up from lab and pilot tests and to run tests successfully. However, only minor effort was needed to deal with critical production issues, with management pressure pushing technology too quickly into production, and with the lack of acceptance standards for the new technologies.

5. Production readiness?

Because the prime contractor's facility was the planned production site, there was no need to transfer the technology to a new facility, with the consequent learning curve. A sizable portion of the development was done by the prime contractor, so they already had a lot of experience with these technologies.

The TADS/PNVS was ready for production. Some of the risk factors, such as scaling technology and running tests successfully, slowed the program down and took considerable effort to overcome. However, other factors required only minor effort.

The three critical technologies forced significant or even serious production process changes, however these changes were not all unexpected since the developer was also the production company. Some of these changes did cause some delay (about 6 months) in production. Components were similar to other production systems, but the system was not. The system-level tests forced them to try to reduce failures by instituting unusual component tests to catch system failures earlier.

6. Importance of technology to Prime?

At the time of the start of development, the prime contractor was planning or had actually started follow-on uses of all three critical technologies. Martin Marietta did have some follow-on contracts that made use of this technology (e.g. U.S. Air Force LANTIRN). Many problems had to be overcome to get the TADS / PNVS operational; but the knowledge gained helped Martin Marietta establish itself in this technology and gain a foothold in a profitable market.

7. Familiarity of Prime with technology?

The laser to sensor bore-sight and line-of-sight (LOS) Stabilization were new and unproven technologies for Martin Marietta. They had used FLIR target acquisition, but this kind of application was new to them. The contractor struggled quite a bit in getting this technology working.

Technology forced production process changes for both stabilization and bore sighting. FLIR target acquisition required significant production process changes. Production acceptance test stations for these technologies were created to test hardware to the system-level specifications. The project office tried to identify component tests and processes that would catch both system-level failures and major subsystem failures. The component-level tests were unique in that they were developed to find system-level failures.

8. Timely problem disclosure?

When there were problems, usually the development team knew immediately where to get outside help. The development team was open about sharing concerns with the Government PM, and the PM shared problems with Army leaders. This open communications helped the Government stay informed and fix problems before they became too big. Any problems the team couldn't handle directly, or with help they could get, the Army was in a position to know about the problem and take steps to resolve it.

9. User support? (Or role of user?)

The TADS/PNVs Program Office had a lot of contact with the Training & Doctrine Command (TRADOC) during development. TRADOC's role is to represent the views of the actual users of the system on the battlefield. TRADOC frequently showed strong support for the project. Occasionally, there were changes in key TRADOC personnel, approximately every three years, but these personnel changes never affected the program much.

TRADOC was consulted on project questions throughout the program, from earliest systems planning, through development, and into the transition to production. TRADOC consistently showed strong support for the TADS/PNVs program throughout the same period.

10. Requirements stability?

The system-level requirements were very stable during development. The threat definitions (detailed requirements) that the TADS/PNVs was required to counter were stable, as well. Requirements changes in the development period can radically change the design. Sometimes the contractor has to get extra money or time to effect these changes.

11. Funding stability?

Project funding was frequently uncertain. The project required almost twice the contracted amount, and the extra money had to be provided by the AAH Program Manager.

The project usually had all the resources needed for development. Occasionally, some minor effort was needed to make changes or compromises because of resource shortages.

Although the Advanced Scout Helicopter (ASH) program, which was leading the TADS /PNVS program, was cancelled, the AAH (Apache AH-64 PMO) was already involved as was MICOM. There was really no affect on the program, other than a change in leadership. Also, instead of needing to meet the demands of two PMOs, the developer now only had to satisfy one, which lowered the technical risk.

12. IPT approach used?

The development occurred before the advent of the formally-recognized integrated product team (IPT) system that is now so prevalent in both Government and industry. However, there was then a realization that integrating people from many disciplines was a useful technique. Though they were not called IPTs, the TADS / PNVs program frequently used multidisciplinary working groups to solve problems. These groups were not formally established, though people from different groups were invited. This often happens in IPTs today – certain disciplines may not be represented either because there is no interest or due to lack of funds to attend IPT meetings.

A similar problem both then and today is that often the membership of an IPT varies. The membership charter may call for one (or more) person(s) from a specific organization, but it may be a different person each time. If this happens, there is no gradual increase in either the working relationship between members or the skill of members. Different people from the same organization may have completely different backgrounds and styles, and can cause disruption when they contradict previous members of their own organization. These changes of direction can be very disruptive.

Also, such teaming was more likely on critical aspects of the program. Performance of the system was critical, so a multidisciplinary team was used.

Multidisciplinary work is not confined to meetings and formal groups. Most of the people on the TADS/PNVs program were in the same building, within a short walk of each other. This fosters quick, informal meetings and also camaraderie and group cohesion. Additionally, many people had worked there for some time, even before the project began. Thus, they were undoubtedly experienced with working together. Some people were in another building in the same area, so it was not too difficult to have face-to-face team meetings on short notice.

The success of any team depends on the leadership of the team leader(s) and also the skills of the team members. During development of the TADS/PNVs, the team leader was good at resolving technical disagreements.

But the path can be rocky in arriving at agreement. When you are trying to integrate a lot of technology and the requirements they actualize, there are often trade-offs. Compromising can be difficult for some people. Occasionally, someone feels that their idea must take precedence, and some good (competing) ideas can be lost. Once or twice, it was necessary to get management help to resolve disagreements.

Usually management reviews were constructive. They had formal reviews at key decision points. The Government PM reported problems that went up to Army leaders. Most of the time, it was easy to get outside help.

In the days before integrated product teams were formally recognized as a key approach to military system acquisition, there were still lots of meetings. These meetings may not have been the most effective solution to solving problems, but they did solve some. The table below lists a range of types of pre-IPT Groups.

Type of Group	Level of Analysis
Staff Meeting	Information passing / Problem solving
Program Status Meeting	Information passing –Very high-level / Critical review
Product / Functional Status Meeting (Low-level)	Information passing –Lower-level / Critical review
Working Groups	Problem Solving and Information passing –Lower-level
Board Approvals: Emergency ECP	Problem solving / Critical review

Table 2. - Pre-IPT Groups

These groups differ from each other in the level of the group, the level of analysis, and whether they include both Government and contractors. Typical staff meetings were simply for information transfer, mostly downwards. It was a way to pass the word to the troops with the least work for the chief. But occasionally, there were problems the boss brought up and people would work on them together, suggesting strategies, evaluating alternatives, offering related information, etc. Both Government and contractors had their own staff meetings, typically with no outsiders.

The typical Program Status Meeting was a contractor to government interchange. It was for passing very high-level information. It really was not possible to solve many problems because of the large number of people present, although action items could be assigned.

Product / Functional Status Meetings were more working level. They were also for information passing, but at a lower level. Occasionally they were conducted like working group meetings involving both Government and contractor participants.

Working group meetings were where lots of problems were resolved. Sometimes all the necessary functional specialties were present. However, most only contained one or two specialties, and other functional types were ignored. Often there were both Government and contractor personnel in these groups.

Because this was a major program for the developer, most key skills essential to the project were available. Some key skills were not on the team itself, but had to be requested when needed. For example, the microwave electronics hybrids and the printed circuit layout design groups supported many different development tasks and teams. Those were both functional groups, and the TADS/PNVS project didn't have enough work to justify keeping members from these areas on their team. However, TADS/PNVS enjoyed as high a priority with these groups as any other project in the company in Orlando.

There was some limited personnel turnover, which can disrupt the schedule of the team; however, many people continued on the project through pre-production planning and testing.

The developer team leader had high technical competence. He had excellent design experience; however, his production experience was mostly on smaller systems.

13. Design to manufacturing and suppliers linkages?

The project team worked and communicated well with internal groups (production, design, and upper management) as well as suppliers. Suppliers were involved in the design process to good effect. Occasionally, smaller prototype components, assemblies, test articles or pre-production parts were passed around to facilitate understanding. Production representatives participated in the design process; and production and design groups met many times to discuss production processes. Manufacturing engineers also reviewed engineering drawings; the more automated verification techniques that are available today didn't exist then.

The TADS/PNVS team had a good relationship with suppliers, at production, design, and upper management levels. Designers asked suppliers for their comments and suggestions. Occasionally, they passed around the prototype models to the suppliers for their comments.

Getting feedback from suppliers often has a good affect on buyer-supplier relations. Instead of being just a customer, the supplier sees the buyer as somebody who produces a useful product. The product has value, and therefore manufacturing and delivering the parts needed to make it, also has value. Additionally, the feedback can generate improvements in use of the supplied parts, or in manufacture of those parts.

Production processes are very important. Design engineers went to the shop floor many times to discuss them with manufacturing specialists. The team members met with the production team on the shop floor during the latter part of the development phase and during the transition to production phase. The production representatives participated regularly in all parts for the development phase.

Though the manufacturing engineers in the production group reviewed engineering drawings, they did not use computational models or analytic tools. Computer tools were not yet widely available, nor were there any of the manufacturing simulation and planning tools which exist today.

During system development, the design engineers and suppliers worked closely together. During joint discussions, they frequently had test articles or pre-production parts to discuss and examine jointly. The suppliers modified their hardware for this specific job to satisfy the developer. They invited suppliers to planning meetings a few times. However, this teamwork did not extend to using computational models or analytic tools.

The design team and technical professionals from suppliers had unscheduled and informal joint conversations about the project during the selection phase and all though

the development phase. Prototypes and parts were used in joint discussions during the latter development phase and the transition to production. Significant effort was needed to overcome suppliers' not meeting delivery commitments.

14. PM's Most Difficult Problem, Solution and Impact?

What was the key issue that the PM had to deal with during the project and how was it dealt with? The key issue involved cost overruns, which were due to several factors. The proposing contractors needed to win a competitive contract based on cost. These contractors downplayed risks brought up by the government, because by fully expounding the risks of their design, they would have shown that their proposal was under-funded; hence, risks were not really explored or mentioned. This scoring of risks was held against the contractor's design, rather than recognizing that the risks are inherent in the government's project requirements. This may have been the best contract vehicle at the time, but it did tend to reward the hiding of information.

It was in the interests of neither the government PMO nor the prime contractor, to have a reasonable program cost at the beginning of the contract. The prime wanted to win the contract in a competitive environment. The government PMO was trying to get the best value for the government.

Reprogramming funds for a program is problematic. Besides the schedule loss while you are going through the effort to obtain funds, there is the schedule loss due to going back and doing risk reduction efforts you should have done earlier, acquiring parts/equipment/facilities on short notice, and also redesigning the system. Each of these four activities has an associated cost. Additionally, there is the cost of materials acquired but no longer needed. Doing all these cost and schedule activities later in the program always costs more than if they were on the program schedule from day one.

Even though the PMO 'knew' that the program probably could not succeed at the initial cost, and that the government would have to provide more money, the strategy was that the profit to the contractor was based on the initial program cost. It is arguable whether this savings in profit to the contractor was offset by the cost of the inefficiency of the total program turbulence and review resulting from cost overruns and reprogramming additional funds. Although making contract decisions based heavily on cost was common at the time, today more contracting decisions are based upon a variety of other factors, including technical parameters.

The TADS / PNVS was recognized as having the highest technical risk on the AAH program, and the system was ultimately successful, though at double the original development contract price. However, significant process improvements are possible in the development and contracting strategy. For example, development contracts are routinely based on more than just cost. Reporting risks can be scored as value-added information. And these risks can be used to evaluate all contracts, not just the contractor who mentioned them – although they may not be inherent in other contractors' designs.

The government and developing contractors should enter teaming relationships early to identify risk areas, and the contractors should be rewarded for this value-added

activity. Finding technical risks later in the program is a common occurrence, but it should be minimized as much as possible. Some programs are cancelled because technical risks grow beyond the end worth of the system. Finding risks earlier saves money, because fixing something is always less costly at the beginning of a program. Going back to the government for more funds, or to the PM, to higher headquarters, or to Congress, could be a decision point for canceling the program.

There were also management complexities that could contribute to cost growth. The TADS/PNVS development contract was a separate contract, not a subcontract to Hughes Helicopters. Both the Martin-Marietta TADS/PNVS contract and the Hughes Apache contract had clauses in them for an Integration and Configuration Working Group. Integration was clearly a potential problem.

Having direct contract with a developer of a subsystem has advantages and disadvantages. It gives the Government more control to have a direct contract, more control over their development processes, and over the contract type. TADS/PNVS was the highest risk item on the Apache development program, and warranted a separate project office. Having this separate office, and a separate prime contract is more work, but it increases the Government's ability to control the risk.

But then there are questions concerning how you integrate the subsystem into the prime contractor's system or vehicle. You can put a clause in the prime's contract that they must integrate the subsystem, and work with the other contractor to do so, but there are still some liability issues that may arise. If redesign is necessary in order to interface the subsystem, then the Government could be liable for the cost. The solution that the TADS/PNVS program chose handled this problem very well.

Prime contractors still use fixed-cost contracts for subcontracts today. The Government currently does not use fixed price contracts for development, believing that development is too high risk. However, subcontracts are frequently where the highest risk parts of the program lie. Often the prime's share of the work, wiring the vehicle, and installing the components, is a much lower risk activity.

If most programs go over cost, then the system is probably too risky. It is better to predict the cost realistically, and commit the appropriate amount. Some budget people advocate squeezing a program a bit to encourage cost reduction efforts, but cutting back by 50% is not realistic. The 5th percentile of the probable cost is too low. Planners should try to target the 40th to 50th percentile of the probable cost. But even then, some programs will go over the contract price, and a program manager or his PEO could have a contingency fund. Starting with a reasonable contract price allows more realistic planning and earlier risk reduction efforts.

15. Test approach used?

In the early stages of the project, the contractor did a Failure Modes Effects and Criticality Analysis (FMECA) on the system. This analysis helped establish the test requirements and influenced simulation efforts. This in turn, drove the design of test equipment and field automatic test equipment, and the same test equipment was also used at the Aviation Intermediate Maintenance (AVIM) facility. Another FMECA result was

the decision that performance tests were to be run under extreme vibration conditions. The production planning efforts during development focused on logistics in an effort to identify the full spectrum of support requirements.

Testing and simulation (T&S) were performed in a variety of settings: T&S of individual components, T&S of components in controlled settings, tests of components in realistic settings, and a hardware-in-the-loop type systems integration simulation laboratory.

The full test strategy included tests of sub-assemblies and of some individual components, performed by Martin Marietta and its suppliers as appropriate. They also verified some components with simulations.

The prime contractor, their suppliers, and government organizations tested some integrated components in a controlled setting. Martin-Marietta and U.S. Army labs performed simulations of some components working together in a controlled setting. They also tested components working together in a realistic setting.

A hardware-in-the-loop type systems integration simulation laboratory was used to check individual components of the system, and to check integrated components in a controlled setting. TADS/PNVS used aircraft simulator test equipment in the aircraft manufacturer's Systems Integration Laboratory.

The prime contractor spent roughly 15% of the total amount spent on the testing and simulation to determine if the individual components of the system worked, 5% to verify that the integrated components worked in controlled setting, and 80% to verify that the integrated components worked in a realistic setting.

Validation work on component and system maturity was done in plenty of time to allow using that information to help the program. Validation knowledge was used consistently to improve components and the system. However, the project didn't do all they could early on to get rid of project risk. The project's test philosophy was to "Break it big early," but sometimes caution prevented using rigorous testing.

Testers and project personnel on TADS/PNVS enjoyed a good teaming relationship. The TADS/PNVS program used the best validation methods available, and they were quick to recognize important lessons learned from this work. The majority of the project validation work was of high quality.

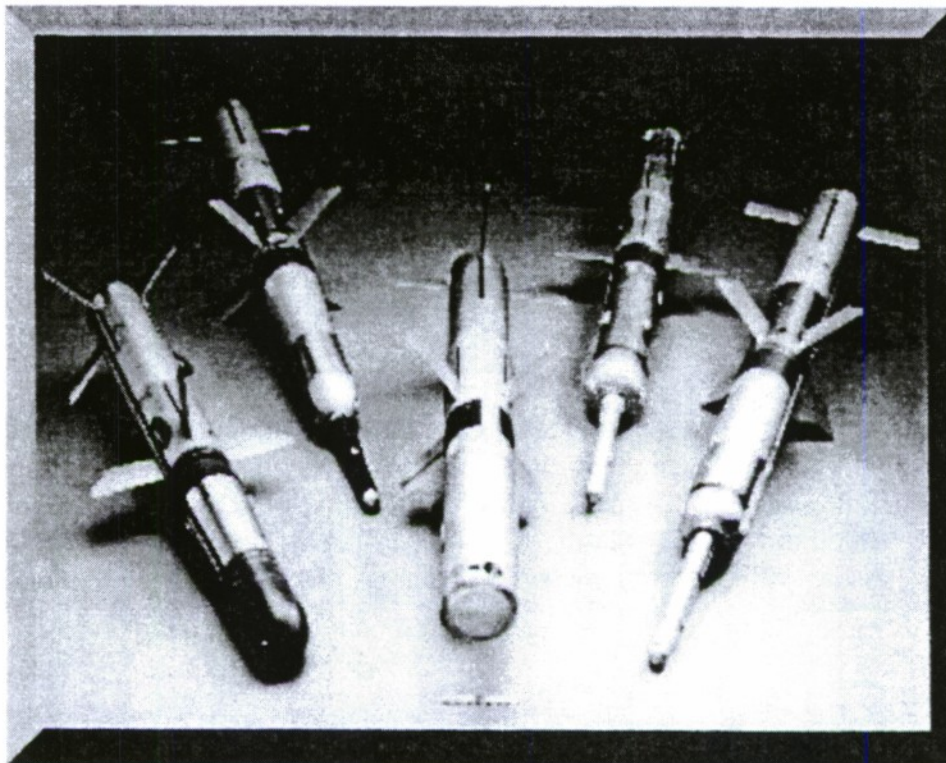
The testing philosophy of the TADS/PNVS program was not very different than those of other defense contractor companies at the time. The TADS/PNVS was a very important part of the AAH program, but very risky. The lower contract funding proposed by Martin-Marietta (and accepted by the government) caused some risky behavior – you cannot allocate money to risk reduction testing if funds are not available.

N
TOW 2A

TOW 2A Case Study



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Introduction

The Tube-launched, Optically-tracked, Wire-guided (TOW) weapon system is a portable antitank heavy assault weapon system. The TOW family of weapons is probably the most proliferated weapon system of its kind in the world. The TOW is primarily an antitank weapon with additional capabilities against other (softer) material targets. This case study will focus on the development and fielding of the TOW-2A weapon and briefly mention its successful use during Desert Storm. This study will particularly examine the factors that made this development successful and detail the lessons learned.

Description of TOW Missile

The encased TOW missile is a cylindrical missile 50.6 inches long and 8.6 inches in diameter, nominal. The missile is fired directly from the case. The missile maneuvers by means of four independently-actuated aerodynamic control surfaces, which deflect a fixed amount in two directions, alternating at a regular rate. Control is affected by variation of the duty cycle of alternation. The missile is roll stabilized throughout the flight. It is yaw stabilized at launch to provide stability in a crosswind. The yaw stabilization is disabled shortly after launch. Guidance commands are received from the launcher via two wires, which dispense from bobbins in the missile. The warhead is detonated upon reaching the target.

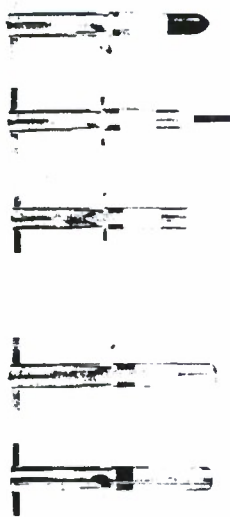
History of Program

The TOW family of missile systems began development in 1966. The TOW-2A version entered into engineering and manufacturing development in 1986. This case study will include a variety of factors that influenced the development, production, and fielding of the TOW-2A version of the TOW family of missile systems. However, in order to familiarize the reader with the family of TOW weapons, the following section will briefly cover the history of the TOW family of missiles.

The following section is extracted from reference 1.

The development of the TOW missile into the family of TOW missiles parallels the development of tank armor. The original TOW missile is now referred to as basic TOW to distinguish it from subsequent types. All of the following variations have been fielded and remain in use by the United States or its allies:

TOW Family of Missiles



TOW Missile

- Produced 1970 -1977

Extended Range TOW Missile

- Extended Range to 3,750 Meters
- Produced 1977 -1981

Improved TOW Missile

- Added Probe for Better Warhead Standoff
- Produced 1980 -1983 and Retrofit

TOW 2 Missile

- Full Caliber Warhead
- Countermeasure Hardened
- Improved Motor
- Produced 1981 -1987

TOW 2A Missile

- Added Precursor Charge to Defeat Reactive Armor
- Produced 1987 -1992
- Produced 1987 -Present for FMS

TOW 2B Missile

- Fly Over Shoot Down Warhead
- Dual Mode Sensor
- Produced 1991 -1997 for U.S. Army
- Produced 1991 -Present for FMS

- a) **BASIC TOW** The original TOW missile has control wires 3000 meters long. The warhead is 5 inches in diameter. (The missile fuselage for all missile types is 6 inches in diameter.)
- b) **EXTENDED RANGE TOW** The wire length is 3750 meters, and is the wire length for all subsequent TOW missiles.
- c) **IMPROVED TOW (ITOW)** The warhead of the Improved TOW included an extendable probe, which extends forward from the warhead as the missile exits the missile case. A crush switch in the probe end detonates the warhead before the warhead strikes the armor. The warhead explosive is improved. The diameter of the warhead remains at 5 inches.

- d) TOW 2 The warhead of the TOW 2 missile is enlarged to 6 inches in diameter completely filling the launch tube. It has an extendable probe. The TOW 2 missile has a thermal beacon, which is tracked by the night vision sight on the TOW 2 launcher. The TOW 2 has a more powerful flight motor than previous types (due to the incorporation of a new smokeless propellant and igniter system).
- e) TOW 2A The TOW 2A adds a precursor charge in the tip of the extendable probe. The intent of this precursor charge is to discharge the armored vehicles' reactive armor before the main charge functions. Ideally, the main charge then only has to deal with the basic vehicle armor.

Public Urgency

Almost immediately after the development and fielding of TOW 2, the antitank threat intelligence community announced the threat of a heavily protected Soviet tank. This announcement followed the public news presentation of an Israeli tank rolling into Lebanon with funny looking boxes attached to the outer surface of the tank. These boxes were explosive reactive armor (ERA) appliqué. This tank was covered with these reactive explosive boxes, which acted as protection against conventional antitank warheads. Because of the potential lethality of these protected tanks, the defense community around the world recognized the urgency of the need for an antitank weapon system to counter the threat. Lieutenant General (LTG) Robert Moore, responsible for Research and Development at Army Materiel Command (AMC) directed the TOW Project Office (PO) at the U.S. Army Missile Command (MICOM) to develop a solution. LTG Moore noted that he wanted a dual path effort (more than one possible solution to the problem) working to field a solution in 24 months.

What to do?

Before the decision was made to (first) upgrade ITOW to TOW-2 and (then) TOW-2 to TOW-2A, the user and development communities conducted studies and competitions between the different Department of Defense (DOD) Research and Development Laboratories, the Department of Energy (DOE) National Labs, Defense Advanced Research Project Agency (DARPA), and missile prime contractors. The user community is a reference used to generically represent the military troops that will use the missile being developed. The development community is a generic term used to represent the engineers, scientists, and their companies or commands involved in the research and development of the missile. The user community believed they wanted a laser beam rider, a command to line-of-sight (put the cross hairs on the target and the missile flies to impact, gunner proficiency is not as much a variable since the gunner's job is over after the target is locked and the missile is fired) weapon system that was faster than conventional anti-tank weapons that would afford the gunner the ability to shoot and scoot. In other words, it would minimize exposure of the gunner. Several of the man-

portable shoulder-fired or crew served weapons systems have a flight time to target of several seconds. The sensors on the threat vehicles recognize a shot has been made and then position the vehicle's armament to return fire to the source of the attack. Therefore, during the time the missile takes to get to the target, the target could be shooting back at the gunner. Consequently, it is an objective to design weapon systems that provide for the least amount of exposure of the gunner to return enemy fire.

General Don Starry, Commanding General, U.S. Readiness Command, told the Defense Science Board that the Army was unable to counter the Soviet reactive armor threat. At that time Dr. Jim Richardson, Director of the DARPA Chemical Energy Warhead Program, had a \$500M armor/anti-armor program with Los Alamos National Laboratory and Lawrence Livermore National Laboratory working the depleted uranium shaped-charge designs, allowing for lighter warheads to do the same job. These competitive developments between all the labs resulted in the use of the phrase "creative tension" within the Government. This "creative tension" between all the developmental agencies was born from the differing opinions on the best warhead choice for the job.

The Under Secretary of the Army at the time, Mr. James Ambrose, his predecessor Dr. Walter LaBerge, as well as the CEO of Hughes Aircraft Corporation (and former Director of Defense Research and Engineering), Dr. Mal Currie were very instrumental in leading this decision process that resulted in an agreement to improve TOW-2 to TOW-2A. Probably the biggest driver in this decision was the "sunk costs" in platforms, training, and logistics support of the existing TOW family of weapons.

Hughes Aircraft Company had already delivered approximately 150,000 rounds of the Basic TOW missile and subsequently has produced over 250,000 rounds of the other TOW variants, including foreign military sales (FMS) to over 40 countries. At the time the decision to develop TOW-2A was made, over 150,000 TOW-2s had been produced. The investment the services had made in the maintainability and supportability of these systems was just too great not be leveraged with the addition of the TOW-2A missile. This meant the existing launchers could be used. This was also a much lower risk approach than starting with a complete new development. This logic was used for both the development of TOW-2 and TOW-2A.

Note: After interviewing the referenced key personnel and researching other related development programs, two quotes stand out here when reading about options for system developers to consider when laying out a program.

"We only spend money on a vulnerability not a susceptibility!" (Coy Jackson - Chief Engineer for the development of all the currently fielded TOW missiles). Most people would use the terms vulnerability and susceptibility interchangeably. Mr. Jackson explains, "Thirty years ago SOME people, NOT ALL, used the words vulnerability and susceptibility interchangeably. They are not the same. Because a system is susceptible to a certain countermeasure does not mean that it is vulnerable. The requirement for a vulnerability is as follows: Vulnerability = Availability + Accessibility + Susceptibility. For example a narrow beam infrared jammer may produce a susceptibility to a missile system and may be mounted on a battlefield enemy tank but it is

too narrow to be effective so the accessibility term is not satisfied. Another countermeasure system may produce susceptibility and be able to get into the optics of a missile system but the countermeasure system is too expensive and fragile etc. In this example the availability term is not satisfied. What I meant was that the TOW PO did not spend money on susceptibilities only. We always looked at the other terms in the equation. After much fighting we would usually agree."

"Options for development include ARCHITECTED DESIGN (Basic TOW), NEW TECHNOLOGY (TOW-2), and EVOLUTIONARY DESIGN (TOW-2A). The key for young engineers is the understanding of the subtleties". (Mr. Mike Schexnayder is an Army Senior Executive Service (SES) member currently serving as the Associate Director for Systems, in the Aviation and Missile Research, Development, and Engineering Center, AMCOM. At the time of TOW-2A development, Mr. Schexnayder was the Chief of the Systems and Warheads Function in the MICOM RDEC.)

The Mission

Three key technologies made possible the development of an effective TOW 2A. First, the warhead section was upgraded to include adding a precursor. In research and development a specific technology is always evolving. For the systems engineer and the program manager knowing what level of evolution a technology has reached gives the decision maker an idea of the associated risks of that technology. This knowledge and understanding supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. For the first key technology of the precursor warhead the component was validated in a relevant environment at the time of this development. That means the basic technology had been integrated to establish that the pieces will work together. This is relatively low fidelity compared to the eventual system. Examples include integration of "ad hoc" hardware in a laboratory. Second, due to changes in the weight and stability of the airframe the guidance section was reintegrated to accommodate the changes in the warhead section. This technology had also been demonstrated in a relevant environment. However, the fidelity of the component technology had increased significantly. This technology had been integrated with realistic supporting elements and tested in a simulated environment. Examples include "high fidelity" laboratory integration of components. Specifically for TOW-2A, the missile guidance equations were changed to reflect weight and center of gravity changes by adding the precursor warhead to the probe. The third technology was the electro-optical counter measure (EOCM) capability. Most of the engineering work on this had just been completed on the TOW 2 program. This technology was a subsystem component that had been demonstrated in a relevant environment. This level of maturity is well beyond the laboratory demonstration. This represents a major step in the maturity of a technology and its readiness. Examples include testing a component in an operational environment. This EOCM improvement was a thermal beacon on the missile being tracked by the thermal night sight. Also, most of the technology based issues

associated with a larger warhead and aerodynamic stability had been solved on the ITOW development. Dr. LaBerge provided oversight and assistance to the warhead integration and aerodynamic performance of TOW-2. Dr. LaBerge was a systems engineer with a structural analysis and controls background. He was instrumental in directing the development of TOW-2. The on-going engineering and testing in support of these two efforts drastically reduced the risks in integrating TOW 2A.

Mr. George Williams is currently a consultant to Colsa Corporation based in Huntsville, AL. At the time of this development, Mr. Williams was the Deputy Program Manager at the TOW Project Office. Mr. Williams retired from civil service as the Program Executive Officer (PEO) for Tactical Missiles. Mr. Williams noted, "Competency at the Army labs was very high". The warhead development, integration and testing was done as a joint effort at the Armaments Research Development and Engineering Center (ARDEC) at Picatinny Arsenal, NJ and the Missile Research Development and Engineering Center (MRDEC) at Redstone Arsenal, AL. The Government already produced TOW warheads at Iowa Army Ammunition Plant (IAAP) and the prime contractor had never developed or produced warheads. Therefore, upon considering the urgency of the need, Army decision makers decided that the warhead section was to be Government Furnished Equipment (GFE) provided to the prime. The corporate knowledge and lessons learned by both entities at this point made this development even lower risk.

Most of the money was spent on missile integration; the technologies had largely been demonstrated as components and subsystems during the development of TOW-2. Historically program managers and senior management responsible for developing weapons systems have taken a position that if a technology works well as a component or subsection then it will inevitably work well after it has been integrated into a system of technologies or components. This assumption has often proven to be wrong and costly. In many developmental programs numerous issues have been identified associated with the integration of the technologies. Developmental programs need to be constructed to allow more time and money for the identification and resolution of system integration issues. Mr. Phil Hooper, who is currently the Chief Engineer at the Close Combat Missile Systems (CCMS) Project Office (the former TOW Project Office) (at the time of this development Mr. Hooper was an engineer assigned to TOW-2A in the TOW Project Office) estimates the Government spent double what they expected to spend on the development of TOW-2A because of the lack of validation and verification of the components and the weaponization of those components early on in the program. These early mistakes forced the expedient teaming of the suppliers, contractors, and Government representatives to solve the integration problems. One of the most valuable resources to the development team is the experience of the senior members in identifying/predicting the system integration issues and leveraging that experience to quickly resolve related issues. Too often the prime item developer wants to work the development of the system with little to no Government oversight. In this case, the critical schedule and costs drivers forced the participation/teaming of all the players (to include the Government engineers) to bring the development back on-line for a successful fielding.

To illustrate an integration issue, during the probe and pre-cursor integration a technical problem was uncovered that all team members decided it made better sense to live with, rather than fix. The missile sometimes experiences a premature warhead function (an "airburst") when the system arms after leaving the launcher. The problem and the solution were identified to the satisfaction of all parties involved. Metal shavings left over from the manufacturing process at IOWA Army Ammunition Plant were causing a short in the electronics. It was discovered that this existed in approximately 2% of the missiles produced. To fix this, a major retrofit would have had to be undertaken. Therefore, the PM and the user decided to not do the retrofit. This problem is not a safety issue only a reliability issue for 2% of thousands of missiles produced. Still today, TOW-2As will experience airbursts when one of the 2% is fired. It is important to note even with the 2% failures, the required/specified reliability for the system was exceeded.

The development team used a "shotgun" approach to solving several of the warhead integration and fuzing issues. In some cases they were never able to isolate single point failures (that is, to identify a root cause) but instead implemented a number of corrective actions for potentially problematic portions of the design and tested for success. The electronics circuit board in the probe used for the delay between the two shaped-charges was the biggest problem. It was believed that the time it would take to determine the root cause failures was not warranted based on the urgency of the development. The experts agreed on multiple fixes that would make the performance better, independent of the specific (root) cause(s) of the failure(s).

The biggest problem facing the PM in this development was the threat definition and stability. The "creative tension" within the development communities was exacerbated by the differing opinions on the warhead design required to do the job and the continually changing representative threat. Throughout this development the Government and contractor engineering communities designed enough adaptability in the systems engineering process to accommodate the necessary changes needed to optimize the performance of the lethal mechanism against the required threat. This flexibility and innovation resulted in a very successful weapon system development.

Mr. Mike Schexnayder was the Chief of the Systems and Warheads Function within the MICOM RDEC; he was most involved with the system integration of a lethal mechanism that met the requirements. "Threat definition was key to this development because the warheads and fuze had to be optimized for certain, representative explosive reactive armors. With the threat definition constantly changing, the scope of the lethal mechanism development would change. Designing the main fuze to survive the high-g shock wave from the pre-cursor detonation forced the Government to invest in engineering fixes to the GFE warhead section."

The required measure for success was based on comparing the amount of penetration that TOW-2 gets against base armor to be equivalent or better for TOW-2A against the ERA and base armor. Remember that the emerging reactive armor threat drove the urgency for

the TOW-2A development. The user and development communities needed a way to score the performance of the TOW-2A warhead section against the performance of the TOW-2 warhead section. TOW-2 was designed to defeat a required thickness of armor and is evaluated against a specification for armor penetration. However, TOW-2A was developed with tandem warhead technology (precursor and main warheads) to defeat explosive reactive appliqué and armor. In other words, the precursor warhead in TOW-2A is designed to defeat a specific type of ERA and then allow the main warhead to defeat the armor underneath the ERA on the threat vehicle. Since new types of ERA were being developed (seemingly faster than warhead technology was being developed) a major issue evolves around specifying the exact threat that the developer is going to design to defeat. This leads to the referenced issue of threat definition and with developing representative range targets for this test program.

The need to see and track targets at night under battlefield obscurant conditions required the development during the TOW-2 program of the night sight tracker and thermal beacon. The infrared spectral range that the tracker operated in greatly increased the system immunity to typical obscurants found on the battlefield. One of the major issues associated with these new developments on TOW-2A was with the concept of "backward interchangeability". They had to make sure that the new components and systems would communicate and work with the early launchers. To their advantage there had been a lot of work done for TOW-2 on the electronics for the night sight to launcher communications.

Another area of concern was the weight, center of gravity, and center of pressure changes to the missile associated with adding the probe with the pre-cursor warhead in it. These changes would largely affect the guidance section and flight algorithms. Most of the engineering for affects associated with probes had already been done on ITOW and TOW-2. However, the pre-cursor presented several differences to include structural issues and spring dynamics.

Some missile guidance problems identified in the TOW-2A Digital Electronics Unit (DEU) were caused as a result of crystals failing at 10,000 "g" shock loads. A large engineering effort centered on root causing the source of the failure and then packaging and manufacturing the fix. This was largely solved by the intercommunications and cooperation with the MICOM RDEC.

Management Observations

This section introduces comments and recommendations that were born from the development of the TOW-2A missile system.

From the point of view of a program manager it could be said that the overwhelming success of this development can be attributed to the communications and trust between the Government and the prime contractor. From the point of view of a technologist the issues were minimized by the prior success of the Basic TOW and TOW-2 efforts.

As stated, the need for communications and trust is crucial. The need for contracting mechanisms that support communications and trust is crucial. If you have an adversarial relationship without trust, your program is doomed to fail!

In the past developers have rushed the fielding of weapon systems based on initial successes of individual components. It was assumed that if the parts worked then the sum of the parts would work.

Don't be misled by component level results early in a development. Trust only system level testing that is representative of a tactical environment before declaring success.
(Phil Hooper) (Summarized by the Author)

Provide incentives for the prime to succeed. Create a contracting mechanism that allows for costing unidentified problems. DO NOT create a contracting mechanism that forces the prime to only focus on the costs and the liability on their part if there is an overrun. Engineers are engineers. They want to develop their technology to succeed and to work in an ethical environment. The primes want to make a profit (certainly not lose money). There needs to be a balance between the Government funding wasted efforts and the primes doing the right thing so that both are not so focused on the budget's bottom line.

Recruit, train, and retain quality engineers that continually train to be system engineers. Find a university that has a master or continuing education program in weapons systems and components and balance that education with job related experience. It seems obvious that to continually lose the experienced people with corporate knowledge without being able to pay for someone to train under them is extremely detrimental to our ability to provide the technology that is needed.

The Process

As discussed, Hughes Aircraft Corporation (HAC) was the prime contractor for the TOW missile system and had been for many years. Therefore, it is no surprise the TOW-2 and TOW-2A developments were won by HAC. It should be noted that all of the TOW-2 and TOW-2A development was full and open competitions. Previously, the MICOM Request For Proposal (RFP) for TOW-2 required extensive work for integrating the night sight and launcher electronics. Mr. Bill Jorden, the Program Manager for TOW development at HAC, suggested a controversial teaming with HAC's arch rivals, Texas Instruments (TI). Mr. Jorden was concerned with the expertise available at HAC to solve the launcher electronics problem: "If we really want to win this thing...TI has integrated trackers to launchers at Redstone, let's team with TI for launcher/tracker effort". After several meetings and negotiations (to build a relationship), this team proved to be a very smart, successful, productive collaboration. The two companies worked out a teaming agreement that resulted in a consortium that no one else bid against. They stayed teamed throughout the development of TOW-2A. Mr. Coy Jackson noted that the Government was very surprised when HAC and TI first submitted a joint proposal for TOW-2.

As would be expected from the urgency of the TOW-2A development, funding limitations were almost nonexistent. Mr. Williams said, "I never had to go to Congress and ask for money". The developers were basically told to build it as soon as they could and tell the Army and DOD leadership how much it would cost. The timeline for this development was clearly established to meet the urgency.

Several process control problems were identified in this program and were aggressively worked and resolved due largely to the open communication between the Government, the prime and the vendors. Mr. Williams offered, "The communications between the Government and the prime were perfect". Even though the concept of Integrated Product Teams (IPTs) had not been coined yet, the environment in which these communities worked is within the generally understood definition of IPTs. According to Mr. Williams, "we were lucky on TOW at this time because we had one of the world's greatest program managers...Bill Jorden". The overarching philosophy that Mr. Jorden believed in was that "if it was good for the Government, then it had to be good for the company."

Note: Mr. Jorden retired before TOW-2A was developed. However, he was a consultant to the TOW-2A development and had left a mind-set and standard for others to follow.

Dr. Lawrence Hyland, Director of Research and Development at HAC, said "our job is to make the PM successful". He gave carte blanche to his program management as long as it was good for the program. According to the interviews for this case study it appears that TI had the same philosophy. (Bill Jorden)

Today's developments are negatively impacting challenges on the primes because the Government and contractors have fewer subject matter experts and systems engineers to know the right issues to work and how to push integrating new technologies. (Bill Jorden)

The technology that was developed and furnished by the Government and the technology developed by the prime and their teams were all very important. Each component was critical to the performance of the system. For example, the probe was developed by a vendor (Fairchild), the Government developed the warhead, and HAC integrated them into the missile. All of the members of the engineering teams were familiar with each of the technologies. The biggest issue for all the members were identifying and solving the system integration issues. The Government technologists within MICOM were heavily involved in this process. Coy Jackson said the Government experts were heavily involved in the system integration of all of the TOW family of weapons which helped make them all successes. Experts in guidance and control, night sights, warhead and fuze, rocket motors and propellants, and electronics were constantly involved in the development and testing. Most of the experts were the same personnel with varying levels of interns and junior engineers in training that stayed with the lab but were always available to the PM for assistance. The level that the technology was transitioned at was in some cases before the technology was mature enough. The prototype of the weapon system should be at the scale of the planned operational system. Before the technology

transitions to program management the technologists should demonstrate the operational capability at the system level. For the most part this effort transitioned at the appropriate times from laboratory, component, and section levels with varying/relative degrees of test results and successes. Again, the lesson here is to keep the technologists in control at each phase until the performance is demonstrated and readied for transition. TOW and HELLFIRE are examples of very successful weapon development programs associated with laboratory support. Examples of programs that failed because the program office and/or the prime item developer transitioned the technology too soon are MPIM, Dragon Generation III, the first M72E4 LAW Rocket, and VIPER. These failures are all examples of programs that the author saw fail due to lack of attention to technical concerns expressed by the Government experts. The technologies were not ready for qualification and fielding when they were forced to try. In these cases the technologists were seen as ultraconservative and ignored.

During the development of TOW-2A the communities involved were fortunate to have experienced system level people available for consultation and oversight when they identified the need for these expertise. As part of the efforts to resolve system issues the younger and mid-career engineers were able to benefit from these lessons for future developments.

"We don't have enough good systems engineers and developers anymore to be successful in all the mission areas we support, both from the Government and contract communities." (George Williams)

The missile systems engineering work was done by HAC in Tucson. The launcher systems engineering was done by HAC in Dallas. Both of these engineering teams were collocated with production facilities. The launcher/tracker systems engineering and integration was done by TI in Dallas collocated with manufacturing. With engineering and productions efforts collocated the resulting exchange of information resulted in only a few minor production related problems.

During early production of the TOW-2A warhead with the probe it was discovered that something as simple as the orientation of the probe assembly could cause spare parts associated with assembly and/or Foreign Object Debris (FOD) to be dropped in and incorporated into the system. Varying spring rates, structural integrity of probe components and assembly steps were all small issues that were discovered and resolved quickly due to the collocation of the engineering and production engineers. Usually when a design transitions from research and development to production the design engineers assume they are done. Typically the productions engineers find design characteristics that make the item much more expensive to produce or such that it cannot be produced at all. Other problems are found in production that might cause safety or reliability problems. Therefore, the fielding of an item is delayed while the two groups work out their issues. In this case the production engineers were involved more early in the design and then the design engineers were close to the production when the issues started to surface.

During the TOW-2A development the design and production engineers were collocated. A great lesson to learn here is the communication and understanding between the users, design engineers, suppliers, vendors, and the production engineers. It is very important that each are involved in the linking/incorporation of each other's requirements. This type of communication eases the transitions and identifies and solves issues early. This corresponds to huge cost and schedule savings.

Role of the User

During the development for TOW-2 and TOW-2A the user community (specifically the U.S. Army Infantry School (USAIS) of the Training and Doctrine Command, (TRADOC)) was very heavily involved in each phase of the development. The TRADOC established TRADOC Systems Managers (TSMs) to help coordinate the users needs to the development community and oversee the development process. The TSM is a military position usually at the Colonel level. [It was observed that the military person(s) responsible for the requirements and following the process, changed numerous times. However, the support and assistance was very much present and appreciated.] A retired Colonel, Paul Ferguson was the continuing representative of the combat developer at the USAIS at Ft. Benning, GA. Mr. Ferguson, was at most of the progress review meetings and provided the necessary user input. The communications between the material developer and the user was open and productive. The participation of a user representative (in this case a civilian employee) that remained constant throughout the changes in military representatives made the user interface work successfully.

"Management at the TOW Program Office believed in telling the user the truth." (Coy Jackson)

Testing

Tandem warhead performance can be tailored around the timing of the detonation between the two charges. Timing differences that significantly impact size and performance of the warhead sections are measured in a few hundred microseconds. The size, shape, formation, length, and speed of a shaped charge penetrator is critical to its performance against ERA and armor. The ability to measure these parameters was not yet available. Instrumentation had to be developed to test tandem warhead technologies. Flash radiograph procedures, equipment, and test configurations had to be developed. High-voltage fire-sets were developed. Sled test fixtures, procedures, and supporting hardware and instrumentation were developed. One of the most specific challenges was to precisely measure the beginning of the timed event.

Early on in the testing there were numerous failures attributed to the environment the system goes through while riding the sled test track. Most of the test procedures developed were centered on isolating and alleviating these issues. Just another example

of relying on only tactical representative flight-tests to declare your technology demonstrated at the system level.

In early testing of the TOW-2A the developers found that the precursor safe and arm (S&A) acted like a blast shield to protect the main charge. A major example of the difference between static testing, individual component testing, and section and system level testing in more representative environments.

As a side note: the safe and arm device used in warhead sections is either mechanical, electrical, or combination of the two, used to provide a means of interrupting (safe) the explosive train of the warhead (when not in use) and then providing a means for arming (arm) the explosive train so that the warhead will function properly when the "fire" command is given. The S&A is as complex as a watch mechanism and/or as the electronics of a computer processor. Quite often, development of approved S&A units has required very long and costly programs. The complexities of research, development, and fielding of S&A units should not be underestimated.

There were specific criteria used as measuring sticks for the continued development and success of the program. In major weapon system development programs millions of dollars in testing is required to prepare a weapon for release as safe and reliable. This release is usually referred to as "type classification". Many different Government agencies are involved and have a say in the type classification of a weapon system. As can be expected everyone involved has a requirement for certain types and kinds of tests to ensure that their area of concern has been resolved or their capability of particular interest has been demonstrated. Therefore, overall test plans are provided for the entire community to approve. Presently this document is referred to as a Test and Evaluation Master Plan (TEMP). It is crucial that all the signature authorities have input and then agree to the program's TEMP. One issue that continually burdened the test community was the perceived changes in the explosive reactive armor appliqué that this weapon was to defeat. Consequently, there were lots of directional changes in the testing until the final configuration was identified.

Mr. Jorden said that the MICOM created, Fly-to-Buy testing was a great force (used with incentives) to keep the prime developer focused on the successful, cost effective, on-schedule production. Fly-to-Buy testing began in 1969 with Basic TOW and is a philosophy based on a weapon meeting all of the specified requirements for reliability prior to the acceptance of that production lot of the system. This is an extremely important phase for the primes. In order to recoup monies spent during the research and development of a system, the prime needs the profits from a production series.

Risks

This section is provided to reiterate and help the reader retain some of the major lessons learned from the investment the Army made in this development.

The TOW-2A program again validated the value of generous funding of risk abatement efforts. In the earlier days of missile development (in conjunction with the German scientists and the space program) all missiles were developed in the Army laboratories and then handed to the prime contractors for production. This greatly reduced the risk associated with weapon performance. This historical environment was what helped in the transition of the TOW family of missiles development from the Government to the prime with Government laboratory assistance. During TOW the warhead and launch motor were developed by the Government and furnished to the primes. All of the other 12 missile subsections were developed by contract. Many of the current programs do not fund for a Research and Development (R&D) effort with anything less than a 100% success based effort. No funding is allocated for risk abatements.

To limit the impact of a success based effort there are some key lessons learned. Identify the trades in technology early needed to meet the balance of cost, schedule, and performance. Keep the technologists in control until the technology is demonstrated at the system level in an operational environment. Do not go to production too early. Keep production engineers, suppliers, and vendors involved during development. Foster trust and communications between all the players. Costs and schedule is always a driver but the TOW PM proved that design for performance becomes cheaper. Primary reason TOW is premier anti-tank weapon.

There is a belief in the development community that the technology should be mature before going to the project offices. However, if the task were presented to the Project Managers/Offices early it would not be refused. Example is the TOW missile DEU. The technology was not mature enough and it took 5-6 years to develop. For a very good reference for the DOD lessons learned in this arena see "BEST PRACTICES", "Better Management of Technology Development Can Improve Weapon System Outcomes", Report to the Chairman and Ranking Minority Member, Subcommittee on Readiness and Management Support, Committee on Armed Services, U.S. Senate, (GAO/NSIAD-99-162) prepared by the United States General Accounting Office, dated July 1999.

In a response to the downsizing of defense budgets the available technology money for labs to use for technology development has almost disappeared. The effects are felt throughout the weapons development community. During the development of TOW-2A the budget was very stable. The only real issues were underestimating the performance of some of the components causing a larger investment than expected. The contractors now have decreased Independent Research and Development (IR&D) monies for proposal-preparation monies. The loser in this atmosphere is the technology and the taxpayer. Most of the R&D programs today must begin with existing, off-the-shelf technologies. When trying to work the politicians to help in technology based funding planning, the return on their efforts is so far out in the future it doesn't help them politically soon enough. Therefore, the American taxpayers along with the political media must have a sense of urgency for the support to be there for defense funding.

Fielding

User fielding issues were more in the earlier design trade-offs with tandem versus canted warheads. The orientation of the lethal mechanism affects the engagement attitude of the missile to a fully exposed tank or one that is in full hull defilade. A direct attack on the front of the tank pushes the requirement for a more capable warhead than if a fly-over shoot-down warhead is used to attack more vulnerable areas on the tank. This is a scenario that supports the full hull defilade, where the tank is hidden from the line of sight and requires a fly-over, shoot-down missile.

During some of the first user training sessions a Lieutenant Colonel at Ft. Benning grabbed two soldiers in line at the mess hall during breakfast and told them to report for training. By 1100 hours they had been checked out as TOW Gunners and both hit 100%. (Neither soldier was a TOW gunners or dedicated weapon specialist of any kind.) They were put in a classroom and briefed on the operation of the TOW missile, shown how to use the targeting system, shown how to track the target, and shown how to fire the weapon. They were taken to the firing range and issued TOW missiles to fire. This illustrates the ease of learning and shooting the TOW missile. Even the sighting and qualifying of the standard infantry rifle (the M-16) takes more training and practice time.

When fielding the TOW-2A the User community experienced very few problems. The gunner training and logistical support tiers were already in place for existing TOW weapons. TOW-2A was a modification that was essentially transparent to the user with the exception of the end-game performance. Cost and schedule associated with the development and fielding was something the user absorbed. They could only wait for the qualification of the new system and then buy as many as they could afford. Since the TOW weapon is a heavy weapon and is predominantly vehicle mounted the opportunity for troop damage is minimal.

Desert Storm (TOW Goes Back to COMBAT)

Prior to deploying to Desert Storm the Army conducted an independent series of environmental and transportation tests associated with the Desert Environment to ensure that the stockpile of TOW-2As were ready for the mission. All missiles passed the referenced testing and were shipped to combat.

During Desert Storm the TOW-2A was used extensively with overwhelming results. There were few reports of problems associated with this weapon system. There were consistent reports coming out of the war applauding the results obtained by TOW-2A's performance.

During the research of this case study the author was told of a report of the efforts of a USMC Reserve Unit in Florida. The report is during the first 24 hours of the war, the TOW gunners in this unit, who had never fired a tactical round before, engaged and killed 20 tanks. The TOW gunners in this unit had only trained with practice rounds.

References

1. *TOW Weapon System, System Characteristics Document, TOW-T24*, Revision D June 25, 1993, Page 80, 'History Of TOW Missile Development' and "Description of TOW Missile", Hughes Aircraft Company

Additional Interviewee Bibliography

Mr. Fred Watson is currently the Chief Engineer for the TOW Fire and Forget Development program for Raytheon (formerly HAC). At the time of this development Mr. Watson was an engineer working the TOW family of weapons for HAC.

Mr. Scott Hill is currently a Senior System Engineer working for the AMCOM AMRDEC, Propulsion & Structures Directorate, Systems and Warheads Function. Mr. Hill was a warhead and fuze engineer in the same organization working the integration of the warhead technologies for TOW-2A.